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REVIEW OF THE USSR ARTICLE ENTITLED, 'NEW RESULTS OF SEPARATED --ETC(U)

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REVIEW ON THE USSR ARTICLE ENTITLED

"NEW RESULTS OF SEPARATED FLOW STUDIES"

(Novyye rezul'taty issledovaniy otryvnykh techeniy), 1973

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Paul K. Chang
The Catholic University
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List of Contents

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REVIEW ON THE USSR ARTICLE ENTITLED

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I. Abstract and background

The USSR article entitled "New Results of Separated Flow Studies" is thoroughly reviewed.

The main purpose of this review is to point out the new developments for separated flow studies in the USSR and to become familiar enough with them, so as to convey to U.S. scientist suggestions of selected subjects for further studies.

This article was published in Russian in the third volume of Russian translation (MIR Publishers, Moscow 1973, pp. 234-302) of the English edition of the monograph of the reviewer "Separation of Flow", Paul K.Chang 1970. Pergamon Press, Oxford) as a supplementary article for USSR scientists.

The authors of this article are, A.I. Golubinsky, V. Ya. Neyland and G.I. Maykapar who referred mostly to the recent Russian papers published in 1966-1972. These were either not quoted or insufficiently presented in this reviewers' English edition.

This article is presented in six sections.

The titles and the essential contents are as follows:

1. <u>Computer calculation of separated flows by numerical methods</u> (Golubinsky).

   The numerical method for the solution of Navier-Stokes equations (N-S equations) at high Reynolds number is presented. For steady and unsteady separated flows the N-S equations are approximated

by a finite difference system to be solved by the use of a computer.

2. Flow separation from wing edges (Golubinsky)

The analytical solution for flow separation from the leading edge and side of the finite span of wing is reported.

3. Asymptotic methods in theory of separated flows and boundary layer interaction with inviscid stream (Neyland)

A new analytical method applicable to flow separation based upon the free-interaction concept is presented in relatively detailed form with supporting experimental results which solves N-S equations by the asymptotic method. Success and limit of its application are indicated.

An improved similarity law is described by taking account of disturbance propagation. The correction of the Chapman-Korst condition at reattachment is suggested.

4. Results of two-dimensional separated flow studies in the USSR using the approximate and the semi-empirical method (Neyland)

The approximate method for the solution of two-dimensional separated flow and the Chapman-Korst method plus the results obtained by applying these methods are presented. The approximate method using integral equation supplemented by the relations connecting boundary layer displacement thickness distribution with outer flow characteristics yields reliable results for the short separated zone, while the Chapman-Korst method yields best results for the developed separated flow zone with constant pressure.

5. Heat transfer to the downwind side of the body with separated high supersonic velocity flow around the body (Maykapar)

Experimental investigation for the high rate of heat transfer on

the reattachment zone over the downwind side of the body at high speed is presented.

Rate of heat flux is measured by the degree of change of color or transparency of the temperature sensitive coating and the lines of reattachment and separation are determined by visualization of the limiting streamlines. The experimental results are given in parameters of M_∞, Re_∞, shape and angle of attack. Tentative conclusions of the experimental findings are summarized.

The application of the technique to eliminate the heat flux peaks by the drooping of the apex or shaping it as a hyperbola is successful.

6. Aerodynamic heating in three-dimensional regions of shock wave interaction with a laminar boundary layer (Maykapar)

   Experimental investigation for heat transfer on the simple body surface on which a simple shaped protruding body is mounted is presented, emphasizing the heat flux peak on the reattachment zone. A comparative study of the heat transfer rate with and without the protruding obstacle is made. The phenomena of separation, reattachment and the maximum heat transfer rate on the plate on which the half-wing is mounted are studied.

For the study of these six sections 149 references are quoted. Among them, 87 references are Russian and 4 are published both in the USSR and elsewhere.

In addition, a number of unquoted references are given for the following subjects:

a) General problems. Computation of separation from a body at angles of attack (outline)

   6 USSR references

   26 Non-USSR references

b) Separation upstream of aperture, obstacle, jets and downstream of obstacle

5 USSR references
12 Non-USSR references

c) Base pressure and thermal flow

14 USSR references
14 Non-USSR references

d) Near wake

12 USSR references
31 Non-USSR references

e) Far wake

11 USSR references
27 Non-USSR references

f) Flow separation between two bodies

4 USSR references
1 Non-USSR reference

These references were published in 1969-1972 after or just before the publication of the English edition "Separation of Flow".
This reviewer used the English translation of the USSR article "New Results of Separated Flow Studies" NASA Technical Translation NASA TT F 17.130 August 1976. pp. 88.
In list of contents, III, Conclusions and remarks, the brief summaries of the content of each section are presented separately, pointing out the new findings and suggesting further studies of the selected topics.

II. Review on the recent developments in the USSR and suggestions for further studies

Review is made separately for the following six sections:

1. Computer calculation of separated flows by numerical methods.
2. Flow separation from wing edges.
3. Asymptotic methods in theory of separated flows and boundary layer interaction with inviscid stream.
4. Results of two-dimensional separated flow studies in the USSR using the approximate and the semi-empirical methods.
5. Heat transfer to the downwind side of the body with separated high supersonic velocity flow around the body.
6. Aerodynamic heating in the three-dimensional regions of shock wave interaction with laminar boundary layer.

The references are cited at the end of each section.

1. Computer calculation of separated flows by numerical methods

The numerical method developed in the USSR is applicable for the solutions of Navier-Stokes equations (N-S equations) at high Reynolds numbers only. For example, for the viscous separated flow over the sharp corner the numerical solution is obtained under the assumption that Re becomes infinite and by applying the asymptotic method and similarity criteria for laminar and turbulent flows. But, for low Reynolds no complete solution is reported in the article.*

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* Article is referred from here on, on the USSR article entitled "New Results of Separated Flow Studies" published in the third volume of the Russian translation "Separation of Flow" Paul K. Chang, MIR Publishers, Moscow, 1973. pp. 234-302.

For the steady and unsteady separated flows the system of Navier-Stokes' equation is approximated by a finite difference system and by the use of the computer, solutions of first or second order accuracy are obtained.

a). Steady separated flow

Dorodnitsyn and Meller (1968,1971) solved the steady two-dimensional incompressible diffuser flow (ratio of width of exit to entrance is two) by the numerical method, evaluating the reduced algebraic equations for each iteration step. The results show that flow reverses in a short region if Re based upon the entrance width reaches 8π and for Re = 32π a very definite stagnation zone with steady reverse circulation occurs. But for Re $> 200\pi$ no solution is obtained because the iteration process does not converge and the sequential approximations oscillate approaching no limit.

This reviewer would like to remark on the experimental findings of Kline (1959) which indicate that for a flow through two-dimensional straight-walled diffuser, the effects of Reynolds number and aspect ratio are negligible but depend on divergence angle and ratio of wall length to throat width. Furthermore, four different flow phenomena occur within the diffuser; i.e., well behaved flow with no separation, large transitory stall, steady fully developed stall and jet like flow.

Therefore, unless the stability consideration is given, the boundary layer theory alone may not solve completely the complex internal flow separation behavior. The solution obtained in a function of Re based upon entrance width and ratio of widths of exit to entrance by Doronitsyn and Meller (1968, 1971) is very limited and its validity to the actual flow phenomena remains to be confirmed.

The studies of viscous separated gas flow by Myshenkov (1970, 1972a 1972b) applying the numerical method for low and moderate Re amounting to several hundred and for Mach number 3-5 confirm the concepts of flow pattern in the separated flow regions sketched in Figure 1 and 2. Furthermore, Myshenkov (1972b) also confirmed qualitatively the existence of a viscous mixing layer. He calculated base flow up to Re = 4.10^3 by applying the approximated N-S equtions and obtained the results of second order accuracy using an explicit scheme.

This reviewer would like to compare the analytical methods developed by Myshenkov with the well-known mixing theory of Crocco-Lees (1952) not only for further understanding of separated flow phenomena but also for the possible improvement of the analytical method.

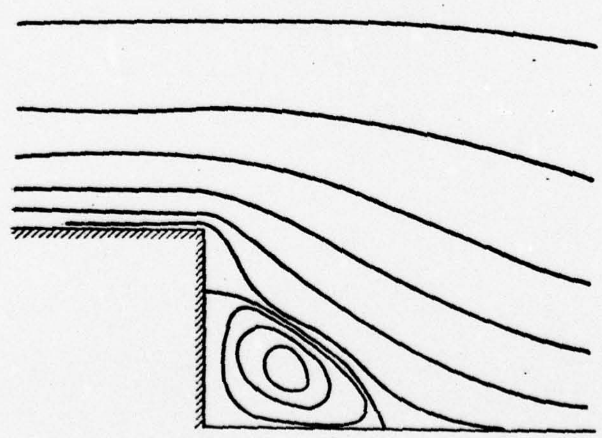

Figure 1. Example of separated base flow calculation. Streamline pattern for M = 5, Re = 800 (Brailovskaya, 1971).

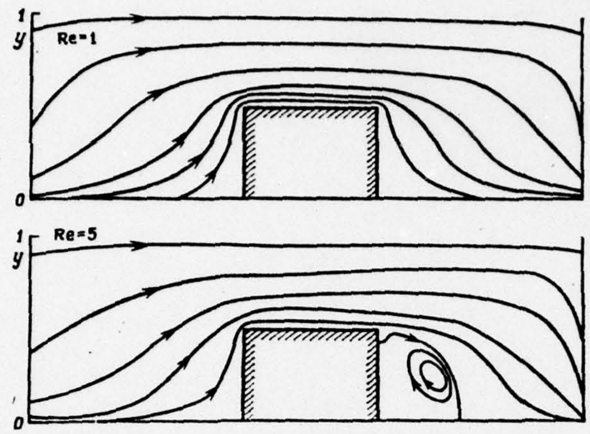

Figure 2. Example of calculation of separated flow around a rectangle. Streamline pattern for $M = 0.3$ and different Re (Myshenkov 1972b).

The viscous flow over the cylinder was not solved by the numerical method due to the difficulties to approximate as nearly as possible the N-S equations and boundary conditions for the external flow. On the other hand, the solution for the steady separated region downstream of a body was obtained by Keller and Takami (1966) and Son and Hanratty (1969), as well as by Barbenko et al (1971), for low and larger Re reaching several hundred including Karman vortex region of Re~40.

This reviewer notes that a numerical solution is available for low Re separated incompressible flow.

Dumitrescu and Cazacu (1970) obtained an analytical solution for the separated flow caused by a flat plate placed at angles of attack by approximating the N-S equation expressed by stream function ψ and using Taylor's series.

The streamlines evaluated by the numerical integration of the approximate N-S equation by a computer in the region of laminar

flow of Re = 30-50 at an angle of attack $\alpha = 45^\circ$ and observed ones by means of flow visualization using floating paper are in good agreement as shown in Figure 3.

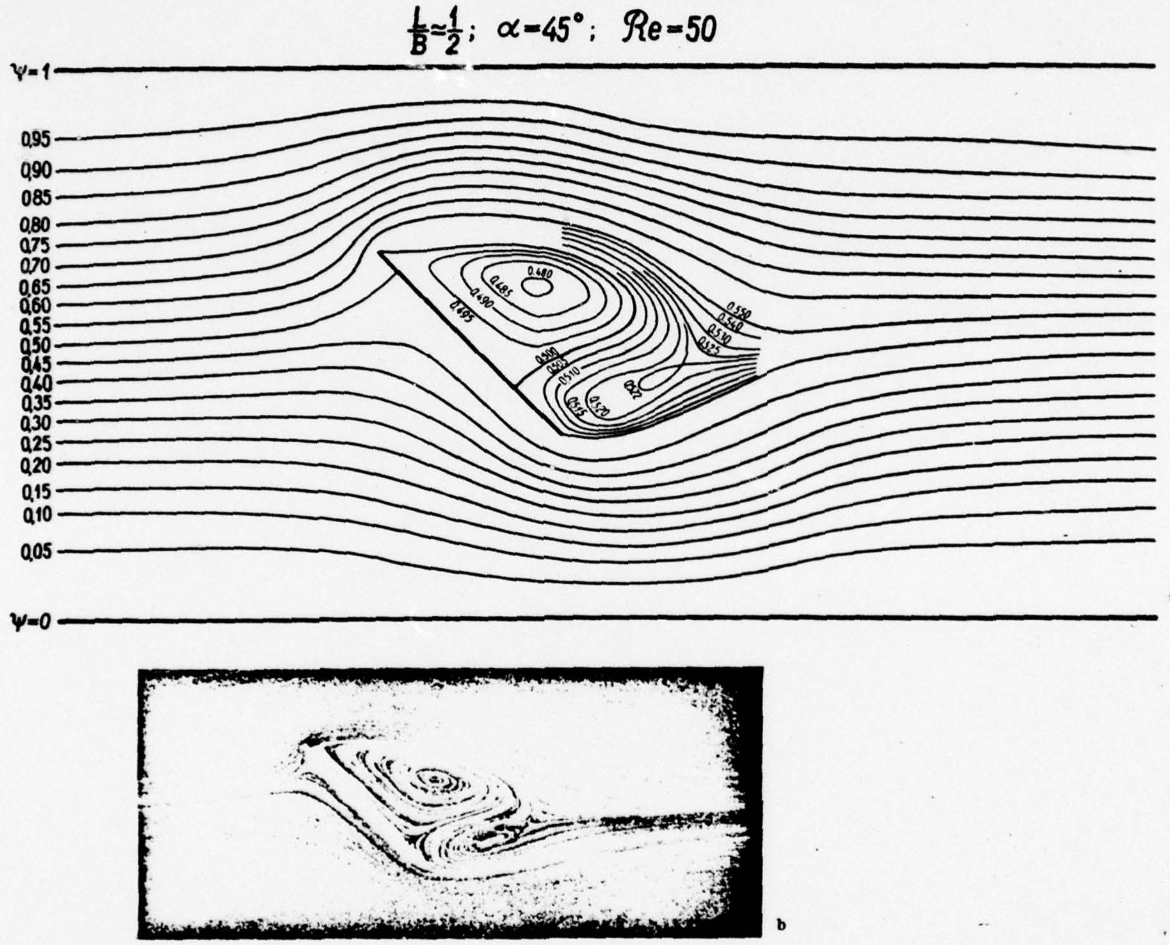

Figure 3. Flow around plate L/B = ½ in mid-channel at angle of attack 45°. L is width of plate and B refers to channel width.
a) computed streamline at Re = 50
b) experimental figure at Re = 45.5
(Dumitrescu and Cazacu, 1970).

b). <u>Unsteady flow</u>

Il'ichev and Postolovskiy (1972) and Belotserkovskiy and Nisht (1971) attempted to solve the separated flow over the discontinued tangential surface by the inviscid flow approach (which is applicable

for high Re) but no complete understanding has been reached because the point of separation is time dependant.

Il'ichev and Postolovskiy (1972) calculated the flow around a circular cylinder with given initial flow asymmetry. The results show that the flow becomes rapidly periodic regardless of the form of the initial asymmetry. The period of vortex detachment from the body is of order r_0/V_∞ (where r_0 is the radius of the cylinder and V_∞ is free stream velocity) as seen in Figure 4.

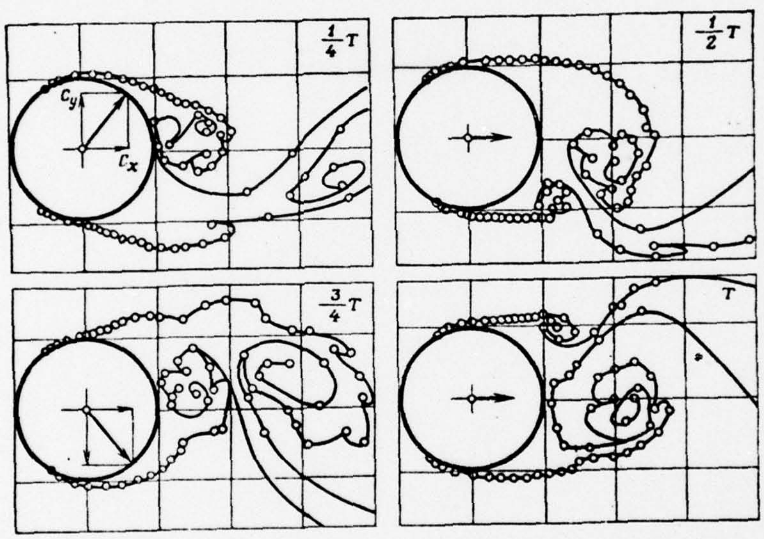

Figure 4. Example of calculation of separated ideal fluid flow around a cylinder. Vortex sheet at different times during a single period T. (Il'ichev and Postolovskiy, 1972).

Golubinsky states that if the location of point of separation on the sharp edged plate at a large angle of attack is known, then the realistic unsteady separated flow pattern over the plate edge from which vortices shed can be determined.

The article further mentions that for flow around a smooth surface such as a cylinder, the location of unsteady flow separation is

not known. However, it should be noted that Schlichting (1960), Goldstein (1938) and Chang (1970) presented the analytical solutions for the unsteady flow separation around a cylinder, sphere and elliptic cylinder in a function of time caused by the impulsive start of motion and constant acceleration.

In section 1 of the article 10 USSR and 5 Non-USSR references are cited.

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Myshenkov, V.I. (1972b) "Numerical Solution of the N-S Equations for Gas Flow around a Rectangle" Izvestiya, AN SSSR MZhG, No.4.

Schlichting, H. (1960) Boundary Layer Theory McGraw-Hill Book Co., 4th edition.

Son, T. S. and T. J. Hanratty (1969) "Numerical Solution for the Flow around a Cylinder of Reynolds Numbers of 40, 200 and 500" J. Fluid Mech. Vol. 35, No. 2.

2. <u>Flow separation from wing edges</u>

The analytical solution of flow separation from the leading edge and the side of finite span at moderate and high angles of attack was obtained by neglecting the viscosity but considering the vortex sheets (tangential discontinuities) shed not only from the trailing edge (Zukowski's assumption) but also from the leading edge and the side.

The calculations of Nikol'skiy (1970) for flow around wings are in good agreement with experimental data confirming the similarity law between three- and two-dimensional flow. Three-dimensioanl steady flow may be reduced to two-dimensional unsteady flow around a flat plate. Thus, an aerodynamic problem of wing of very small aspect ratio can be solved.

This reviewer believes that the article refers to Hayes' (1947) unsteady analogy for unsteady flow in one less dimension with corresponding boundary conditions and shock relations. The coordinate X is interpreted as the time and all other variables as the actual physical quantities. The unified super-hypersonic similarity rule is known as follows: the flow fields for a family of affinely related bodies are similar if the similarity parameter $\beta \cdot \delta$ is the same for each body where $\beta = \sqrt{M_\infty - 1}$ and δ is any measure of thickness. Van Dyke (1954) points out that an unlimited number of equivalent forms of reduced variables can be produced by multiplying any power of the similarity parameter.

Additional lift of the rectangular wing due to flow separation from the side edges is proportional to the 5/3 power of the angle of attack and 1/3 power of the aspect ratio. These findings are in agreement with investigations reported in Ref. 5-8, Chapter 12 of this reviewer's book, <u>Separation of Flow</u>.

The well-known computational method of flow over the slender finite span wing exposed to incompressible flow by replacing the vortex sheet with discrete horseshoe vortices was generalized to calculate the non-linear problem of flow around a wing. The vortex sheddings originating from the trailing edge as well as from the leading edge and the side of the wing were considered by Belotserkovskiy (1968) and the computations at moderate and large angles of attack agree with experimental data as shown in Figure 5 confirming qualitatively the similarity law.

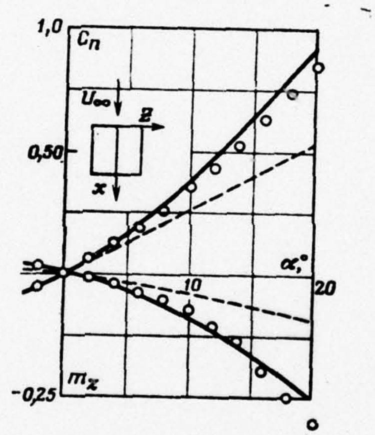

Figure 5. Comparison of calculated and experimental aerodynamic coefficients of rectangular wing with aspect ratio 1. (Belotserkovskiy, 1968).
0 = Experiment;
- - - = Linear Theory.

In section 2 of the article each two references of USSR and non-USSR are cited. Much of the information was obtained from non-USSR sources.

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Belotserkovskiy, S. M. (1968) "Calculation of Flow around Arbitrary Planform Wings in Wide Angle of Attack Range" Izvestiya, AN SSSR MAhG No.4.

Hayes, W. D. (1947) "On Hypersonic Similitude". Quart. Appl. Math. Vol.5, No.5, pp. 105-106.

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Van Dyke, M. D. (1954) "A Study of Hypersonic Small-Disturbance Theory" NACA TN 3173.

3. <u>Asymptotic methods in theory of separated flows and boundary layer interaction with inviscid stream</u>

The problems of free interaction are investigated extensively by Neyland (1968) and Stewartson (1969) based upon the asymptotic approach to N-S equations by taking $Re \to \infty$. The solutions obtained are significantly different from those of the classical boundary layer theory.

This reviewer wishes to remark on free-interaction as follows:

The free-interaction occurs because the compression is directly responsible for the thickening of the boundary layer and its ultimate separation is generated by the outward deflection of the external flow caused by the thickening itself. The pressure rises due to the fact that free interaction at the separation, in the absence of heat transfer is proportional to $C_{f_0}^{\frac{1}{2}}$ where C_{f_0} is skin friction coefficient immediately upstream; i.e. $C_{p_s} \sim C_{f_0}^{\frac{1}{2}}$. Therefore, even for the case of a zero or negative pressure gradient in inviscid flow theory at sufficiently large Re in the real flow boundary layer interaction with the supersonic stream occurs upstream of separation causing a positive pressure gradient downstream.

The free-interaction is defined by Chapman et al (1957) as interaction free from direct influences of downstream geometry. The pressure rise to a separation point in supersonic turbulent as well as laminar flow is a free-interaction phenomenan not dependent upon the mode inducing separation, as shown in Figure 6.

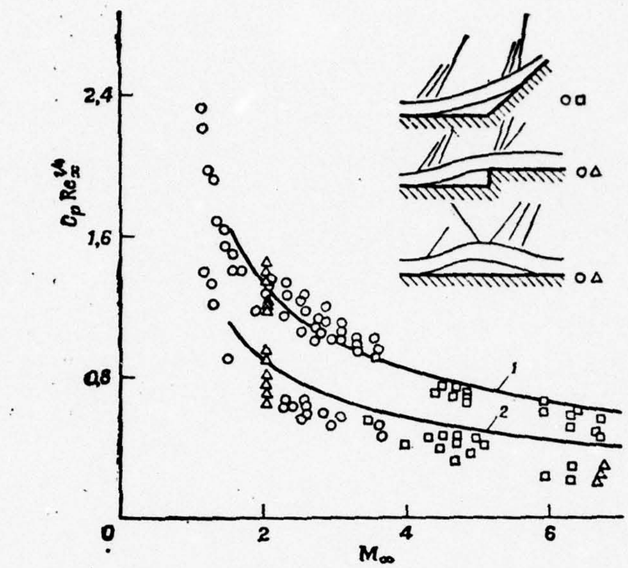

Figure 6. Comparison of theoretical and experimental pressure coefficients at the separation point and in "plateau" region of the developed separation zone.
_____ = Calculation (Neyland, 1968, 1971),
Experimental data presented in
(Erdos and Pallone, 1961) ;
O = Chapman, Kuehn, Larson (1957);
□ = Sterret, Emory (1960);
△ = Hakkinen, Greber, Trilling, Abarbanel (1959);
1 = Plateau region;
2 = Separation point.

In the boundary layer theory in order to set up a uniform asymptotic approximation two flow regions are necessary--one is described by Euler equation which is hyperbolic for $M > 1$ and another is viscous thin boundary layer which is parabolic. But with this set up the information on disturbance propagation is not obtainable, although the solution of complete N-S equation may provide its information.

According to Neyland (1968) and Stewartson (1969), the asymptotic solution of N-S equations yields different results in three regions near the separation point of order of length $Re^{-3/8}$. The first, the outer region is described by the first approximation and linear supersonic flow theory. In the second region of transverse dimension $Re^{-1/2}$ velocity profile is the same as the

case of the first approximation in the undisturbed boundary layer upstream of the free-interaction region. Since the disturbances are small in the first approximation, pressure distribution is not affected. The third region is the near-wall viscous flow layer of thickness $\sim Re^{-5/8}$.

The variation of its thickness induces a pressure gradient in the external supersonic flow causing separation. The governing equations are those of conventional incompressible boundary layer but since the pressure gradient is not given a priori it must be determined in the process of solution using the compatibility conditions with outer supersonic flow. Based upon these conditions and Ackeret's linear supersonic flow theory, the pressure gradient is determined relating to the second derivative of displacement thickness. Since the boundary layer equation is referred to the higher (second) derivative of the displacement thickness which is the longitudinal variable of unkown function, it is necessary to specify another edge condition, in addition to the initial and boundary conditions on the body surface and at the outer edge of the boundary layer. However, because the derivative with respect to the longitudinal variable is total rather than partial, it is sufficient to specify a single constant, in this case the separation point instead of a function.

Even the first approximation (Euler equation) yields a good agreement with experiment data of the pressure coefficient at the separation point and in the plateau region as indicated by Neyland (1971a). The asymptotic flow governed by its local nature can be solved in a universal manner and formulated in the similarity law by converting the physical variables. If the asymptotic

flow is written in non-dimensional variables, then it becomes independent from all parameters such as Re, M and temperature, etc. The second approximation taking account of the pressure differential in the vertical direction with respect to streamwise flow direction, approximates more closely the real flow behavior. Thus, all approximate methods based upon boundary layer equations (for example integral method) cannot yield a more exact solution than the first approximation.

The asymptotic theory of Neyland (1968) and Stewartson (1969) applied to the neighborhood of the separation point in three regions can be used to a broader class of flows by taking account of effect of rapid change of boundary conditions transmitted to upstream due to local interaction of the boundary layer--more precisely the slow viscous flow in the neighborhood of the wall--with inviscid outer supersonic flow. Since the mechanisms of upstream propagation of disturbance is the same for all flows of this type, analytical solution can be obtained based upon the concept of free interaction.

Neyland (1971b) applying the free-interacton theory studied the compression flow around the corners and weak shock impingement to the boundary layer with pressure differential of order $Re^{-1/4}$. The results show that in the first approximation the boundary-value problems for these two types coincide everywhere ouside a region of length $\sim Re^{-1/2}$ if the incident shock wave amplitude and wave reflection angle are suitably chosen.

Neyland (1971b) also computed the critical pressure differential causing boundary layer separation and generalized the similarity laws for these flows obtaining numerical solutions for several

flows including those with separation zones of length $\sim Re^{-3/8}$.
The advantages of the similarity law applied to free-interaction are as follows:

The similarity law is general and is given in simple forms of equations and boundary conditions. The first approximation yields a satisfactory solution if the disturbance amplitude is not too large.

The contribution of variable physical effects are clearly understood and can be applied to a broader class of flows stimulating further development.

It is this reviewer's opinion that the thorough study of the similarity law and asymptotic method developed by Neyland and Stewartson not only leads to a clear understanding of the similarity law for free-interaction but also to the successful applications for the following 4 examples of supersonic flows:

1) flow over flat plate
2) flow over wedge
3) flow over flat plate at angle of attack
4) flow over flat plate with pressure gradient

as sketched in Figure 7.

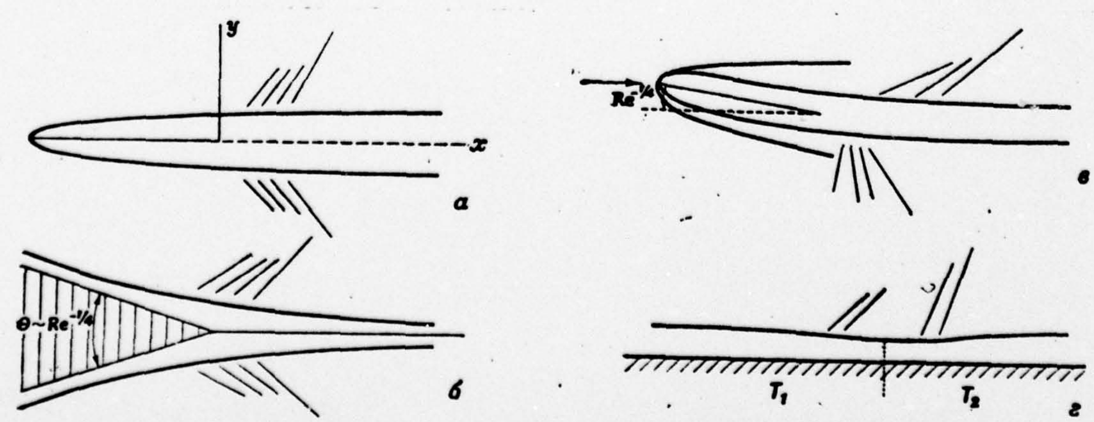

Figure 7. Supersonic flows described by free-interaction theory.

More details of these four examples are described in the following pages.

1) For flow over the flat plate, the non-slip condition $u(x,0) = 0$ for $x > 0$ is replaced by the symmetric condition of $u_y(x,0) = 0$. Neyland (1968) investigated the disturbance amplitude and dimensions of regions to which the disturbance propagates. Reduction of shear stress to zero on flow axis leads to acceleration of the stream filaments passing near the plane of symmetry causing a rapid change of displacement thickness and inducing a pressure gradient. Simple estimates using equations of continuity, momentum and linear supersonic flow theory show that near the end of the plate a local free-interaction flow region of pressure differential $\Delta P \sim Re^{-1/4}$, $\Delta x \sim Re^{-3/8}$ is formed. A negative pressure gradient is induced near the end of the plate and pressure recovers in the wake, but at $\Delta x/Re^{-3/8} \to \infty$ the pressure gradient becomes zero.

2) Flow over wedge is similar to 1), thus analogous results are obtained.

3) For flow over the flat plate at the angle of attack, an analogous pattern compared to 1) is valid if the angle of attack is small amounting $\alpha \sim Re^{-1/4}$, as Brown and Stewartson (1970a) found. In this case flow turns through the angle $\pm\alpha$ ahead of the plate end on upper and lower surfaces. At sufficiently large α, flow separates and the critical pressure differential to cause separation is somewhat larger compared to the flow around a corner formed by two walls because the pressure gradient becomes negative due to flow leaving the plate as the case of $\alpha = 0$.

4) For flow over flat plate with pressure gradient the pressure differential $\Delta p \sim Re^{-1/4}$ is induced on the length $\Delta x \sim Re^{-3/8}$ according to the linear supersonic flow theory. This differential pressure ΔP in turn influences the near wall layer. This result is obtained also by the first approximation. The major part of the boundary layer affected by $\Delta P \sim Re^{-1/4}$ changes the magnitude of displacement thickness in an order of $Re^{-3/4}$. This change of magnitude is taken into account in the second approximation.

Goldstein (1948) and Stewartson (1958) studied the singularity arising in the solution of the boundary layer equations near the separation point for given pressure distribution. This reviewer would like to note that at the laminar separation point $\partial^2 u/\partial y^2\big|_{y=0} = 0.082$ as Thwaites (1949) indicates. This quantity is large but finite, although mathematically it may be considered as infinite. However, Sychev (1972) shows that in the vicinity of the separation point, a free-interaction zone of the same type of supersonic flow exists, as Neyland (1968) indicates, but there is also a difference because for the outer inviscid flow region, instead of the linear supersonic flow theory, it is necessary to use the solutions of classical jet flow theory. Local flow separation is caused by the pressure gradient induced by free-interaction. It is of interest to study Sychev's (1972) investigation of the free interaction zone in the vicinity of separation and Thwaites' (1949) result to contribute to the analytical solution in the neighborhood of separation referring to Goldstein (1948) and Stewartson (1958) and the survey paper of Brown and Stewartson (1970b).

In the USSR, analytical studies were made for a very large local pressure gradient. Neyland and Sychev (1966) presented the basic asymptotic theory for the flow with a very large local pressure gradient. As a typical example, the expanding gas flow near the corner of a body at a supersonic speed is cited. Some details of this analytical study are given as follows: The corner has a small rounding with a small radius of curvature of order of undisturbed boundary layer thickness ($Re^{-1/2}$).

Near the corner the pressure and slope of the velocity vector vary in large magnitude over a small distance and in a region of thickness $\sim Re^{-1/2}$ the subsonic velocity rpofile prevails and magnitudes of u and v are of same order. On length $\sim Re^{-1/2}$ in the vicinity of the corner, the longitudinal and transverse pressure gradients have the same order of magnitude. These values are evaluated from the equations of continuity and momentum. If $Re \rightarrow \infty$ then the N-S equation becomes the Euler equation whose solution does not satisfy the non-slip conditions on the surface. Therefore, on length $\sim Re^{-1/2}$ another thinner layer is considered in which the principle N-S equation terms associated with viscosity have the order of magnitude of inertia terms and viscous layer thickness is proportional to $Re^{-2/3}$. The required boundary conditions are obtained by the use of well known principle of asymptotic matching of solutions in different characteristic regions. Thus, the required boundary conditions can be established by matching the solutions for the local regions having longitudinal and transverse dimensions $\sim Re^{-1/2}$ and the outer supersonic stream yields outer boundary condition for the local region. The profile of the parameter "undisturbed approaching stream" at $(x/Re^{-1/2}) \rightarrow -\infty$

is established by matching with the solution in the undisturbed boundary layer. Because of the small thickness of the viscous flow region, for locally inviscid flow the "nonpenetration" condition must be satisfied on the surface of the body: $v = 0$. Solution of this boundary-value problem enables the determination of the velocity and pressure distributions at the outer edge of the viscous local flow. The general method to solve this problem as well as the equation of boundary layer development due to an accelerating flow from an infinitely distant point $(x/Re^{-1/2}) \to -\infty$ were proposed by Neyland (1966).

The existence of a transverse pressure gradient and centrifugal forces in the local inviscid flow region lead to redistribution of that part of the vortical flow near the body surface. In this case the pressure may be less than far downstream of the turning region and this effect increases with the increase of the body contour turning angle and causes the flow separation probably on the segment where the pressure increases to the limiting value as Neyland and Sychev (1966) indicate.

The asymptotic theory applied to compute the flow upstream of the base of the body and in the base separation region by using the Dorodnitsyn method of integral relation indicates that even by the first approximation the pressure distribution along the body surface is determined quite exactly in a good agreement with experimental data.

In order to describe completely the disturbance propagation upstream of the base, it is necessary to study the longer region $Re^{-3/8}$ with pressure differential of order $Re^{-1/4}$ by free-interaction theory, in addition to region of length $Re^{-1/2}$ with pressure differential ~ 1.

The so-called "blocking"effect of the disturbance emanating from the base upon reaching the speed of sound on the local inviscid flow stream line adjacent to the body surface is reported by Neyland (1967) and Matveyeva and Neyland (1967). The acceleration of flow upstream of the base increases the friction stress sharply while the thermal fluxes to the body increases to a lesser degree. The acceleration of the flow in the local inviscid region takes place equalizing the magnitude of pressure upstream of the base to that of the base, when the ratio of the pressure on the body surface upstream of the disturbed flow region and in the base separation region is less than the sonic differential amounting to $[(\gamma + 1)/2]^{1/2}$, where γ is the ratio of specific heats. In this case the expansion of the supersonic stream filament takes place as a result of the contraction of the sonic stream filament lying to the body surface. However, when the total pressure differential reaches the above mentioned critical value, the Mach member at the body surface (in the locally inviscid part of flow) reaches sonic value and further expansion of the upstream flow of the base is impossible and a centered rarefaction wave forms near the corner.

Further reduction of the base pressure does not influence the flow ahead of the base.

This reviewer notices that at low speeds the wake behind a blunt body is time dependent, the vortices are well developed, and the dominant frequency is proportional to the free stream velocity. But as the free stream Mach number increases and flow becomes compressible, a drastic change occurs in the structure of base region and the violent periodic behavior evident at subsonic flow

pattern is established. Further increase in Mach number at large Reynolds number produces no qualitative change in the near wake region at these high speeds, the viscous flow fields are at the well-known "hypersonic freeze" conditions and the wake properties become independent of Mach number if $M_\infty \cdot \delta$ is sufficiently large where δ is the angle between the free-stream direction and a tangent to the local body surface (Dewey, 1964).

Neyland states in the article that Stewartson (1970) did not consider this fact as he compared it with the experimental data of the pressure differential downstream of the turning region up to 0.32 of the initial value at $M_\infty = 2.75$.

Matveyeva and Neyland (1967) found that pressure reduction measured upstream of the corner amounts to 60% of the total pressure differential in a good agreement with their conclusion.

Neyland further states in the article that Stewartson (1970) did not consider the formation of the locally inviscid flow region and Stewartson concluded that the pressure drop ahead of the corner reaches 90% of the total pressure differential based upon the study of the free-interaction region alone.

It is this reviewer's opinion that the phenomena of disturbance "blocking" thus described is a significant subject to be studied. Clarifying the difference of findings reported by Neyland and Stewartson this reviewer notes that a particular phenomena, the so-called "sticking distance" was reported by Lin (1953) as a significant feature of the transition of wake flow downstream of a slender body. The transition downstream of a slender body appears to "stick" at a fixed distance from the body due to dynamic stability. The reason for such occurance of this

"sticking distance" is believed to be in the propagation of instabilities by subsonic disturbance. Both "blocking" of the disturbance and the "sticking distance" are phenomena of separated base region.

The investigation of compression flow with a large local pressure gradient to cause the separation is carried out in the region of the order of the magnitude of pressure variation on length of order of the boundary layer thickness $\sim Re^{-1/2}$. As an important example of such flow phenomena, the flow field in the region of semi-infinite supersonic jet attachment on a plate sketched in Figure 8 is investigated. The attaching flow is described by Euler's equation as the first approximation. At the outer edge the conditions of compatibility with outer flow are satisfied while on the body surface the normal velocity component is zero.

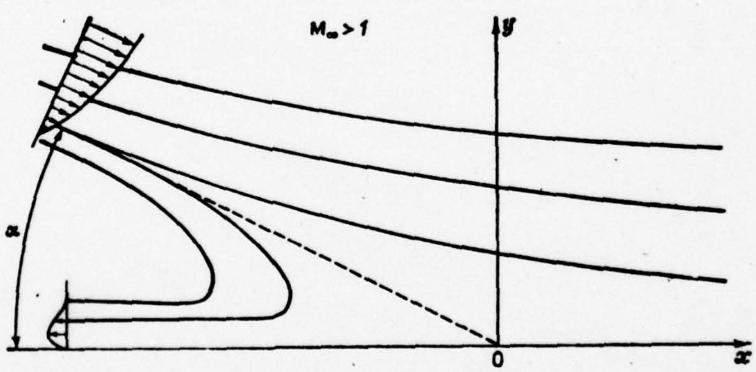

Figure 8. Flow scheme in region of semi-infinite two-dimensional supersonic jet attachment to the surface of an infinite flat plate.

The solution of the first approximation shows that the stagnation pressure p_0 at the end of mixing zone on the dividing stream line which impinges on the surface must be equal to static pressure p_∞ at large downstream distance, but in reality $p_\infty > p_0$ by a magnitude of $\sim Re^{-1/4}$ affected by viscosity, and this is a

definite analogy with the Chapman-Korst condition of the reattachment zone. If Bernoulli's integral of inviscid flow is applied then $p_0 > p_\infty$ but the monotonicity theorem of vortex flow predicts the shift of the critical point to an infinitely distant point downstream if $p_0 = p_\infty$.

Neyland (1970a) shows that the condition of $p_0 > p_\infty$ is impossible in a wide range of initial and boundary conditions, because for the condition of $p_0 > p_\infty$ in the right of critical point an inviscid flow region must exist where no reverse flow occurs. This fact does not satisfy the compatibility with inter-surface for $(x/Re^{-1/2}) \to +\infty$.

Thus the analysis is carried out in the following procedure: applying the first approximation, locally inviscid flow solution is obtained satisfying the condition of $p_0 = p_\infty$, not containing the critical point. Then by studying the asymptotic behavior of disturbance decay, including the flow region of $x \sim Re^{-3/8}$ where the characteristic pressure differential is of order of the $Re^{-1/4}$ and also pressure increase reaching the limiting value of p_∞, the critical point is located. The solution is described by the equations of free-interaction theory. Thus, Neyland considers that the Chapman-Korst conditions should be corrected by order of $Re^{-1/4}$ (pressure differential causing boundary layer separation is of the same order). Neyland's important conclusion is that the critical point in the reattachment region must be in the viscous flow region.

It is this reviewers view that correction of the Chapman-Korst analysis suggested by Neyland (1970a) should be carefully investigated in order to solve the reattachment flow problem.

Neyland also studied heat transfer at the reattachment zone obtaining a good agreement with experimental data.

For the computation of heat transfer in the narrow lower part of the local inviscid flow region, USSR scientists investigated the dominating effects of viscosity and thermal conductivity applying the modified Dorodnitsyn method of integral relation and using two strips as the edge conditions of these regions, numerical solution is obtained for the inviscid flow.

The resulting magnitude of pressure distribution is lower than that of experimental value, because only the locally inviscid region is considered, therefore in order to improve the agreement with experimental data it is necessary to obtain the solutions in the free-interaction region.

Neyland examined the applicability of the asymptotic method for the developed separated zone and found that although important results have been obtained for very simple flow, it is difficult to apply the asymptotic method for the developed separated zone. Investigations of Prandtl and Batchelor for steady incompressible flow region bounded by closed stream lines at $Re \to \infty$ show that if the gas flow rate within such a zone is larger by order of magnitude than the flow rate in the narrow boundary layers at the edges of the region, then within the zone as $Re \to \infty$, there is inviscid flow with constant vorticity. For the simple particular case of constant pressure along a boundary, Batchelor determined the magnitude of the vorticity using the conditions of flow steadiness in boundary layer. These conditions are generalized for non-isobaric incompressible flow by Neyland and Sycher (1970) and for compressible flow by Neyland (1970a).

This reviewer would like to mention the simple Squire's (1956) model for cavity flow. Employing the idea of Batchelor (1956), Squire proposed to divide cavity into an inviscid care inside and boundary layer region outside as seen in Figure 9.

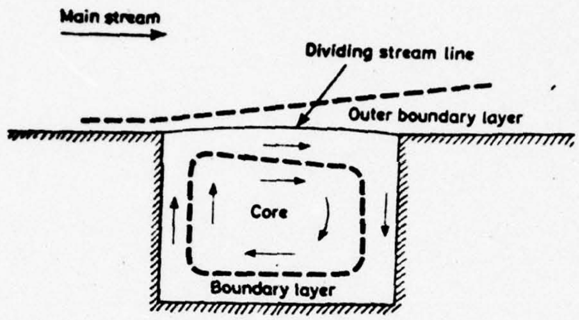

Figure 9. Cavity flow with core. (Squire, 1956).

The motion in the cavity is maintained by the sheer stress of the outer flow acting on the stream line boundary of the cavity. In many cases, although the core may be small compared with the extent of the boundary layer, it may be postulated that the concept of cavity flow consisting of an inviscid core surrounded by a boundary layer is a useful one to solve the problem of a steady incompressible flow region boundary by closed stream line. In the USSR the separated region upstream of a flap at supersonic speed has been investigated applying the asymptotic method. By assuming that the inner part of the separated zone consists of only a single region bounded by a closed stream line, the following four regions of flow pattern are considered:

1. Vicinity of the separation point of length $O(Re^{-3/4})$. Universal solution is obtained for this region.
2. Region of flow reattachment on the deflected flat wall where the difference of pressure differential amountin $O(Re^{-1/4})$ compared to the Chapman-Korst condition.

3. Region of inviscid reverse-circulation flow where velocity is small but does not become zero as $Re \to \infty$ and vorticity is nearly constant.
4. Two boundary layers which separate the inviscid reverse circulating flow from the outer inviscid flow and from the wall surface.

Applying the first approximation and based upon this model if the vorticity and temperature in the reverse flow region are determined then it is possible to evaluate configuration of separated flow zone and heat transfer. In general, the secondary vortices are formed, but their influeneces on the general flow pattern, separation zone shape and pressure are frequently insignificant. Neyland presents in the article analytical procedures linking upstream and downstream regions of separation point citing Brown and Stewartson's (1970b) and Catherall and Mangler's (1960) works. Brown and Stewartson (1970) surveyed the analytical and numerical evaluations of boundary layer equations in the separation zone where singularity is thought to exist. At the point of separation and in the regions of upstream and downstream of the separation point, by taking the pressure and the derivative of the boundary layer displacement thickness, all regions of the separation zone are linked together.

Catherall and Mangler (1960) used an artificial procedure as follows: First numerical integration of the incompressible boundary layer equation is carried out for given pressure distribution in the usual way. But at a small distance upstream of separation point, instead of pressure, boundary layer displacement thickness distribution in the form of a second or third degree

polynomial is assumed and pressure is determined. In the flow region near the separation point boundary conditions change rapidly, therefore the pressure distribution at the outer edge of the boundary layer cannot be considered to be given. The procedure described here is an inverse problem and by taking such a procedure it is possible to link the attached and separated flow regions and even the small reattachment zone.

This procedure yields the solution for a particular case and yields no unique solution downstream of separation, nevertheless, it gives a solution which corresponds to the reverse flow critical point of the separation zone. In order to find a unique solution it is necessary to specify an additional boundary condition, a constant. This may be the base pressure or separation location which can be evaluated from the conditions of compatibility with the solution determining the flow further downstream.

Neyland states in the article disturbance propagation is to be included for the improved similarity law and considers the following parameter families. With the usual boundary conditions there exists two single-parameter families of non-self similar boundary layer equations, in addition to the well-known self-similar solutions obtained by Less and Stewartson. These parameter families are presented by Hayes and Probstein (1962), as follows:

$$f(\xi,\eta) \sim (\eta) + \xi^{1+a} A_1 f_1(\eta) + \xi^{2(1+a)} f_2(\eta) + \cdots$$

$$p(\xi) \sim A_0 \xi^{-1} (1 + A_1 \xi^{1+a} + A_2 \xi^{2(1+a)} + \cdots$$

where ξ, η and f are conventional Dorodnitsyn-Lees variables defined by:

$$\xi = \frac{2\gamma}{\gamma-1} \int_0^x p\,dx, \qquad \eta = (2\xi)^{-1/2} \int_0^y p\,dy$$

and u = $\frac{\partial f}{\partial \eta}$ with conventional notation.

The first terms represent the self-similar solution.
The non-trivial solution exists only for the "eigen value" a and is defined within an arbitrary constant, for example A_1.
The subsequent terms are found uniquely for given A_1 from the solution of the linear non-homogeneous system of equations.
Depending upon the sign of A_1 the pressure for the non-self-similar solutions is everywhere greater ($A_1 > 0$) or everywhere less ($A_1 < 0$) that obtainable from the self-similar solution.
The flows for positive and negative A_1 are termed as compression and rarefaction flows respectively.
Kozlova and Mikhaylov (1970) obtained analogous results for a triangular wing and a yawed flat plate when the approaching flow is not normal to the leading edge of the plate. The intensity of disturbance propagation upstream increases with the increase of the yawed angle. For the final solution of flow over a triangular wing, it is necessary to find out whether the boundary condition is satisfied in the symmetry plane or not. The eigen value a is the criterion of upstream disturbance propagation intensity as shown from the analytical results of Neyland (1971b), Provotorov (1973) and Kozlova and Mikhaylov (1971) and seen in Figure 10.
Since with the increase of a, its effect decreases, for flow over a flat plate if gas is injected through the body surface then the effectiveness increases while with cooling of the surface the effectiveness decreases markedly as Kovalenko (1972) and Neyland (1972) found.
A very important question is the formulation of additional boundary condition to be used for the unique solution. For example, as Neyland (1970b) indicates for flow near a flat plate base, if

the downstream base pressure is given, it is necessary to select the solution of the one-parameter family for which the pressure at $x/\ell = 1$ is equal to the given base pressure. The symbol ℓ refers to plate length.

For the compression flow the separation point moves upstream with the increase of base pressure and the solution for the flow downstream of separation may change due to the presence of reverse flow. Neyland suggests further studies for the solution of compression separated flow in the article.

The solution for the rarefied flow by non-self-similar concept leads to a singular point at which the friction stress on the body and absolute magnitude of the pressure gradient become infinite. However, the pressure remains finite and positive equal to p_1. For the base pressure $p_b \ngtr p_1 \,[(x/\ell) = 1]$ the equation is solved in the same way as the case of compression flows.

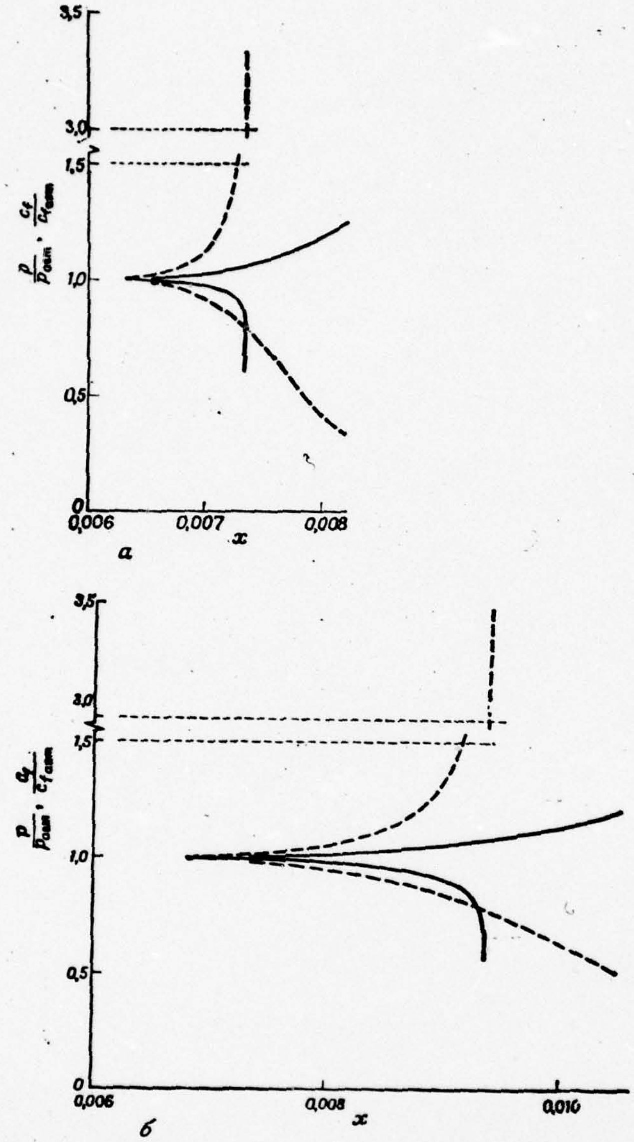

Figure 10. Distribution of pressure and local friction drag coefficient on flat plate for strong hypersonic flow interaction with laminar boundary layer (Neyland, 1971b). a - γ = 7/5; $\alpha \approx$ 49.6; b - γ = 5.3; a $\approx$23.
--- = p/p_{ss} ; - - - = C / C ; γ = ratio of specific heats;

p , C = values of parameters for self-similar-solution;

x-dimensionless length for one of the non-self-similar-solution.

In this region of p change of base pressure influences the pressure distribution over the entire suface of the body.

If $p_b > \left[2/(\gamma + 1)^{\frac{\gamma}{\gamma-1}} \cdot p_1 \right]$ then the solution on most of the body i.e., for $0<x/\ell<1$ is fixed and has a singular point at the end. This means that near the base a high local pressure gradient region exists in which the pressure on the body varies from p_1 to p_b over the distance of order of the boundary layer thickness.

Variation of p_b in the noted limits influences the flow only in the local region. If base pressure is reduced further to $p_b < \left[2/(\gamma+1)^{\frac{\gamma}{\gamma-1}} \cdot p_1\right]$ then it no longer influences the flow because at the end of the local inviscid flow region the flow velocity near the surface becomes sonic and disturbances do not propagate upstream. In this case, the solution differs significantly from the self-similar solution, particularly near the base.

Neyland (1970b) shows that the boundary value problem for the flow on a flat plate with $\chi = \infty$ where χ is viscous interaction parameter defined as $\chi = M_\infty \tau$ is variant relative to some single-parameter group of affine variable transformations except for the condition at the trailing edge. This fact enables the reduction all non-self-similar solutions of problems to "standard" solutions corresponding to compression and rarefaction flows.

The new similarity law developed in the USSR is more general compared to that developed previously be Lunve (1956) and Hayes and Probstein (1959). These available laws are not complete because no disturbance propagation upstream is taken into account although these are useful for regions with small a disturbance propagation effect.

Kozlova and Mikhaylov (1971) further studied the similarity law taking account of disturbance propagation obtaining a good agreement with the experimental data of Gorislavsky and Stepchenkova (1971) and Gorenbukh and Kozlova (1973) for the regime of strong interaction of hypersonic flow as shown in Figure 11.

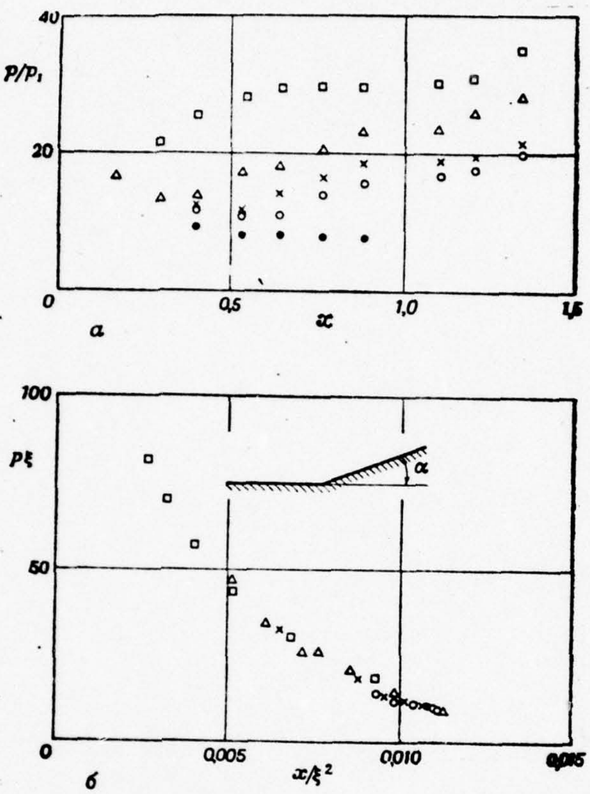

Figure 11. Experimental verification of similarity law for flows in the regime of strong interaction of hypersonic flow with boundary layer with account for disturbance propagation upstream; $M = 23.3$; $Re = 1.9 \cdot 10^4$ (Neyland, 1970b and Gorislavskiy and Stepchenkova, 1971).
a) Experimental results; b) Same results in similarity coordinates: • $\alpha = 0°$; ○ $\alpha = 10°$; × $\alpha = 11°30'$; Δ $\alpha = 12°$; □ $\alpha = 20°$.
ξ = Dorodnitsyn variable.

The asymptotic methods are applied to problems of flow around small obstacles or irregularities located on the bottom of the boundary layer by Zubtsor (1971), for incompressible flow and by Bogolepov and Neyland (1971) for compressible flow.

The results obtained by Zubtsor show that if the characteristic dimension is of the order of protuberance height, the first approximation reduces to the solution of the Euler equation. For the excessively sharp reduction of the protuberance height (steeper than $|x|^2$).

The solution of Euler's equation contains a reverse flow region upstream and downstream of protuberance.

The supersonic flow over small protuberance for various flow regions and for all possible combinations of geometric parameters and local boundary layer thickness, was studied by Bogolepov and Neyland (1971) formulating corresponding boundary values and similarity parameters.

The conclusion reached is as follows: The marked increases of friction stress and thermal fluxes to the body surface take place at larger distances exceeding the order of magnitude of the characteristic obstacle dimension.

For the determination of the onset of separation upstream of an obstacle whose height and separation zone legth are of the same order of magnitude at distance $\sim b$ (b is height), it is necessary to solve the complete incompressible flow N-S equations, although the outer flow is supersonic with specified boundary conditions.

If the obstacles are slender then the determination of separation onset and separation development becomes simplified considerabley to the solution of Prandtl equation.

In these problems the pressure gradient is not associated with the second derivation of the stream function with respect to x, in this case. An interesting and particular flow phenomena around a slender obstacle is noted at high Re when the Euler's equations are valid for the most part of the disturbed regions as follows:

The sign of the pressure disturbance caused on the forward part of the obstacle depends on a parameter equal to the ratio of the obstacle cross-section over to the characteristic boundary layer section area, $\sim Re^{-1}$. If this parameter is small, the obstacle

induces rarefaction since the interaction propagates only to the subsonic part of the boundary layer profile.

Conversely, if this parameter is large, compressive disturbance occurs, and the outer supersonic stream has the primary influence on the interaction.

The verification of the similarity laws by experiment and favorable comparisons of pressure data obtained by theory and experiment are shown in Figure 11 and 12.

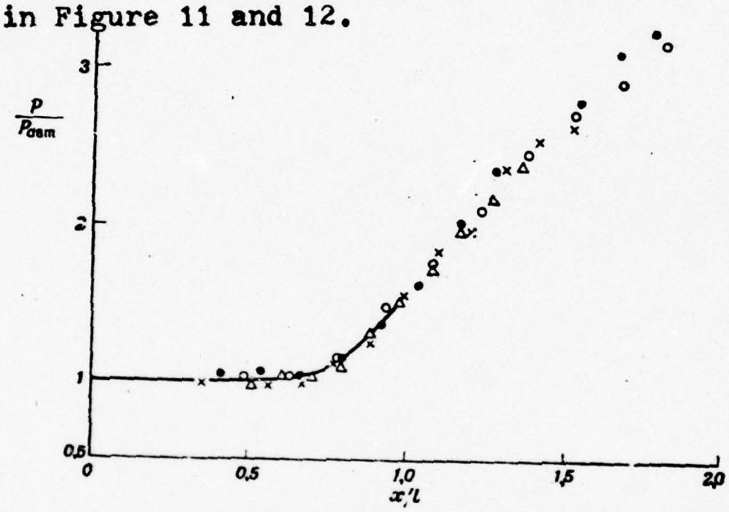

Figure 12. Comparison of theoretical and experimental data on pressure distribution on flat plate with flap for strong interaction of hypersonic stream with laminar boundary layer. M = 24.2; x = 10-16. (Gorenbukh and Kozlova, 1973).
ℓ = distance from plate leading edge to flap;
p_{ss} = pressure for the self-similar solution; _____ = calculation
(α = deflection angle of flap mounted on aft part of plate).

This reviewer notes the analytical solution by Lighthill (1953) which determines the position of separation and configuration of separating stream line for incompressible laminar and turbulent upstream flow over an obstacle mounted on a flat plate.

This solution is based upon the conformal mapping technique. The first approximation in the form of Euler's equation may lead to determination of the separation zone configuration as Neyland states in the article but its accuracy of prediction remains to

be examined by comparing it with Lighthill's result.

In section 3 of the article, there are 28 USSR and 26 Non-USSR references cited (3 references are quoted as both USSR and Non-USSR references).

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4. Results of two-dimensional separated flow studies in the USSR using the approximate and the semi-empirical method.

Various approximate methods are classified into two types: first and second.

The first type uses various forms of integral equations and the relations obtained from the boundary layer equation, while the second type corresponds to the Chapman-Korst method.

The first type is considered first. This approach is a direct extension of the well-known method for separation free boundary layers. For the solution, integration of a system of non-linear ordinary differential equation is carried out thus the distribution of functions through the boundary layer is not obtainable by this system. Hence, this system is supplemented by the relations connecting boundary layer displacement thickness distribution with the outer flow characteristics.

The choice of the family of parameter distribution profiles through the boundary layer thickness and also the relations for the calculation of the outer inviscid flow is important in order to obtain satisfactory results.

In the USSR for the analysis of laminar flow a single parameter family of power-law velocity and stagnation enthalpy profile in Dorodnitsyn variables as well as the single-parameter family of velocity profiles obtained by self-similar boundary layer equations are used.

Applied to the separated zone upstream of a flap where the pressure is nearly constant this analysis yields results in an agreement with experimental data if the separated zone is not excessively long.

For the analysis of turbulent flow involving separation the integral methods are used applying Crocco-Leé's theory because the integral method is better suited for turbulent flow than laminar flow.

Since the basic closed system of exact equation for the turbulent flows has not yet been obtained, it is not possible to develop the more exact method. Due to the high intensity of the turbulent mixing with the nearly constant pressure region it is often difficult to compute by a unified scheme and results to be obtained are less definite, although the separated flow on the spike is exceptional. Supplemented by empirical data, the turbulent flow solutions for the separated flow regions, for base pressure and for the critical pressure differentials are obtained.

Gogish and Stepanov (1966) computed base pressure, near wake and jet flow around bodies and separated flows in channels. Gogish and Stepanov (1971) determined the characteristics of the pseudo-shock in the transonic region from supersonic to subsonic flow in a long channel. In this region instead of normal shock, the system of complex weak shock is formed and turbulent flow separated.

The second type which corresponds to method of Korst (1956) and Chapman (1951) yields the best results for the developed separated zone with constant pressure not only for turbulent flow but also for laminar flow.

This method is well-known and this reviewer presented it in detail in his book, Separation of Flow, 1970, Pergamon Press.

In the USSR, Minyatov (1961), Tagirov (1961,63,66) used this approach and computed base pressure on rear facing step placed to turbulent flow. Bondarev and Yudelovich (1960) Yel'kin et al (1963)

Neyland (1963) and Neyland and Sokolov (1964) studied base pressure on simply shaped bodies.

Yel'kin et al (1963) indicate that the well-known principle of flow stabilization as $M_{\infty} \to \infty$ holds for separated zone at hypersonic speeds and established that the base pressure on slender wedges depends on the well-known similarity parameter $M_{\infty} \tau$ where τ is dimensionless thickness of wedge.

For the solution of the complex problem of separated flow on smooth surface (separation point is not know a priori) Chapman-Korst condition alone or any modification of this condition is not sufficient to determine the separation zone length and separation point. Therefore, in order to evaluate the separation position it is necessary to use another algebraic relation connecting the pressure in the separated zone with local boundary layer characteristic upstream of the separation point.

Such relations are often called separation criteria.

The presentation of this reviewer's book, Separation of Flow, concerning the methods to determine the separation zone length and separation point based upon experimental data, model and analysis may lead to the necessary information for separation criteria. In the USSR, Neyland (1965) presented a general approximate method for the solution of separation on a flat plate upstream of a flap in supersonic flow and Yudelovich (1965) determined the base pressure on a sphere. Murzinov (1970) computed gas temperature in the separated zone based upon the isobaric separated zone concept. Tagirov (1966) developed a method to estimate the time necessary to establish a stationary flow in the turbulent separated zone assuming that the slowest

process of establishment of stationary flow in the base region is turbulent mixing.

This reviewer found that in the USSR the methods of Crocco-Lee and Chapman-Korst are applied for various separated flow problems confirming further the applicability of these methods.

In section 4 of the article 23 USSR and 3 non-USSR references are cited.

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5. Heat transfer to the downside of the body with separated high supersonic velocity flow around the body.

In the USSR, the high rate of heat transfer on the reattachment zone of downside surface of a body at high speed and its control techniques are investigated experimentally. For the two-dimensional and axisymmetric supersonic speed it is well-known that on the reattachment zone the rate of heat transfer is very high compared to that on its surrounding area. For the three dimensional separated flow the occurance of thermal flux peak has been found experimentally. But its parametric study in M_∞, Re_∞, shape and angle of attack has not been sufficiently carried out, despite the fact that a suitable control technique to reduce the large amount of heat transfer on the reattachment zone exceeding by an order of magnitude compared to its surrounding area is urgently needed to safeguard the flight vehicle.

The significant feature of three-dimensional separated flow compared to the two-dimensional and axisymmetric separated flow is as follows: If the separated region of two-dimensional and axisymmetric flow is closed and within its boundary, flow circulates and the dividing stream line reattaches to the body surface then this flow phenomenon is similar to jet flow.

But for three-dimensional flow a "longitudinal" flow whose direction remains the same, is superposed on the circulating flow and the separated region may not be closed forming the "spiral flow".

The magnitude of thermal flux is measured by Ardesheva et al (1972) Borovoy et al (1968), and Jones and Hunt (1964) as exemplied in Figure 13, by the degree of change of color or transparency of the temperature sensitive coating independently of pressure.

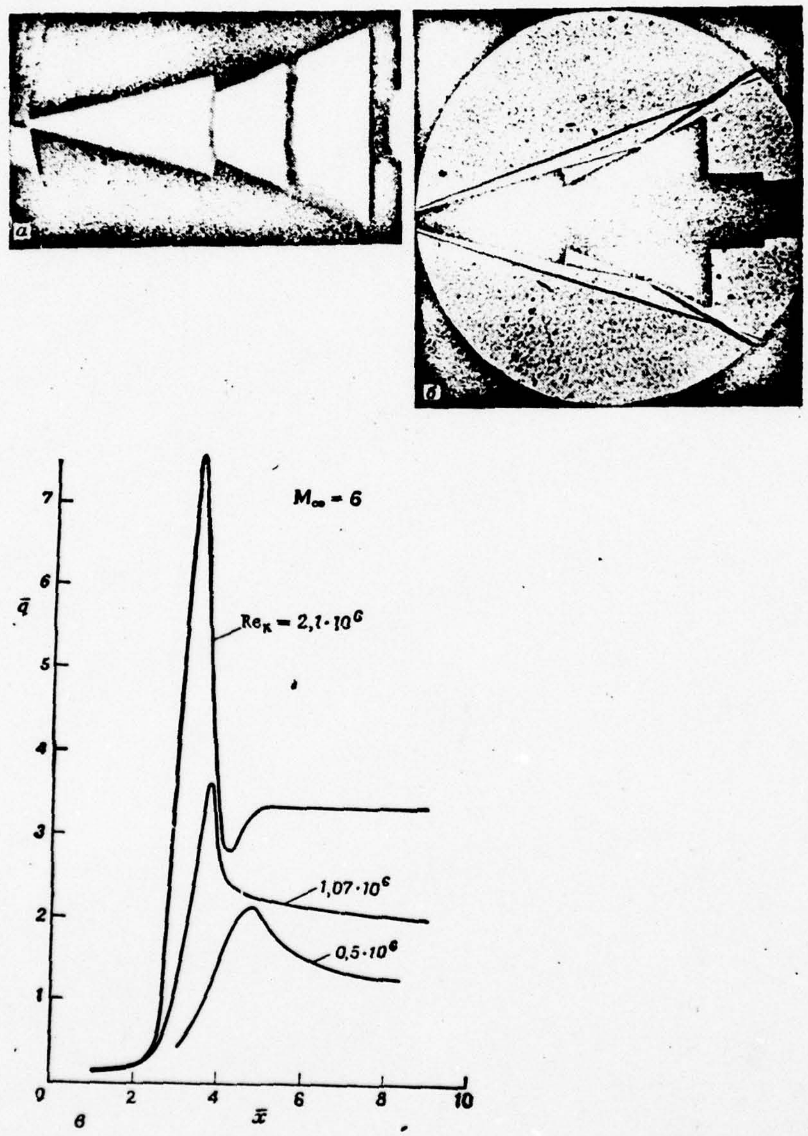

Figure 13. Cone with rearward-facing step. (experiments by Bryazhko).
a) Temperature-sensitive coating; b) Shadow picture; c) Thermal flux distribution along the generator; x-distance from separation point on cone, referred to step height; thermal flux q is referred to the thermal flux at the separation point (laminar boundary layer); Reynolds number Re_K is based on the parameters at the separation point.

The lines of separation and reattachment are determined by the limiting stream line observation. If the limiting stream lines meet along a line tangentially then such confluence line is considered the line of separation and if the limiting stream lines spread along a line then such a line is defined as the reattachment line, although these definitions are not exhaustive ones to obtain the complete understanding of the complex three-dimensional flow involving separation and reattachment.

The thermal flux peak behavior on the flat side of blunt semi-cone was investigated by Borovoy et al (1968) and Borovoy et al (1968a) and Borovoy and Ryhkova (1969).

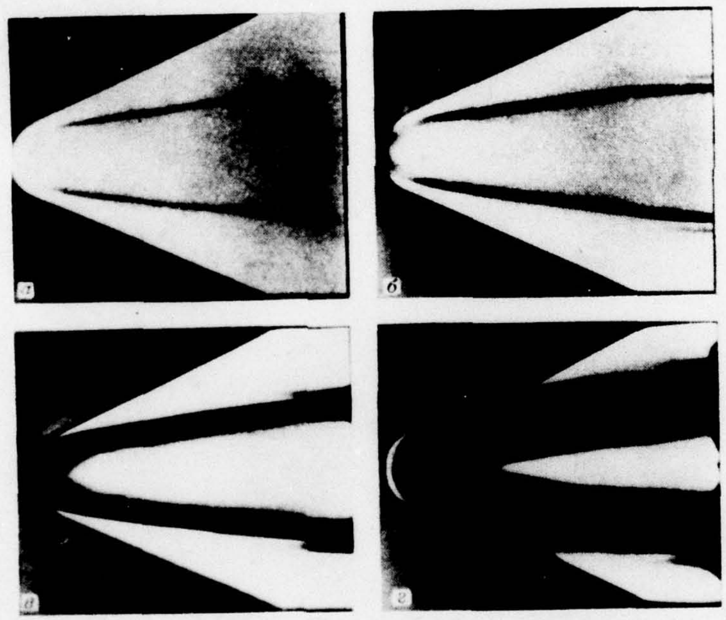

Figure 14. Semi-cone $\theta_k = 24.3^\circ$. Coated with temperature sensitive paint, angle of attack $\alpha = 0^\circ$ (flat side facing downstream), $M_\infty = 5$, $Re_{\Lambda,\infty} = 1.1 \cdot 10^6$, $Re_{L,\infty} \cdot M_\infty^{-6} = 70$. (Borovoy et al , 1968a) a - t = 0.8 S; b - t = 3 S; c - t = 12 S; d - t = 48 S.

As seen in Figure 14, two narrow bands of the maximal thermal flux starting from the point of the hemisphere with the cone was discovered with a model coated with temperature sensitive paint. Red color of this paint changes to black at $T = 338.2^{o}$. Furthermore as shown in Figures 15 and 16, these lines of the maximal thermal flux are those along which the limiting stream lines spread. The length of the limiting stream line is a measure of the magnitude of shear stress.

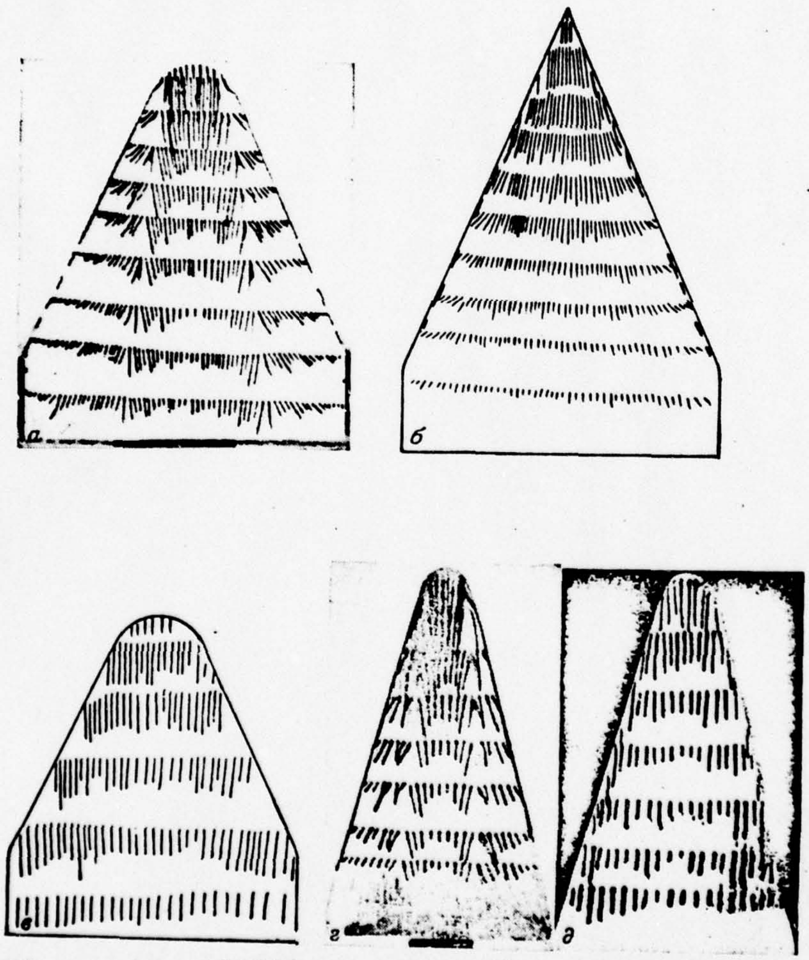

Figure 15. Limiting stream line patterns for semi-cones, $\alpha = 0^{o}$. (Borovoy and Ryzh, 1969).
a) Blunt; b) Pointed; c) Blunt; d) Pointed
e) Blunt; L = Length.

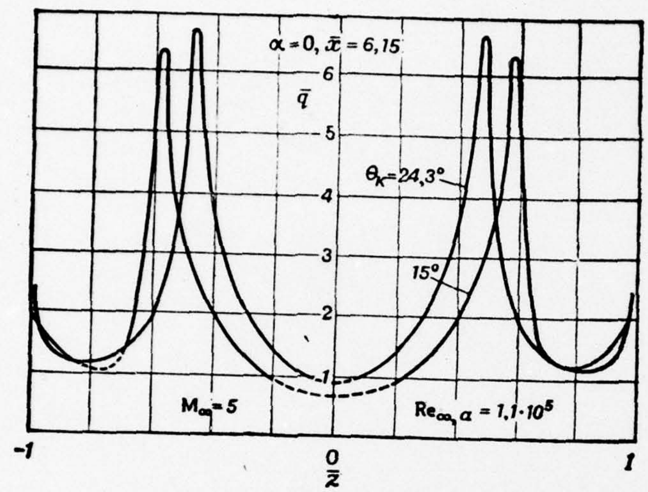

Figure 16. Thermal flux distribution over cross-section of flat side of blunt semicone. (Borovoy and Ryzhkova, 1969). $\bar{x} = x/a$; a = tip radius, thermal flux $\bar{q}$ is referred to the thermal flux to the flat plate (laminar boundary layer).

It is found that the radius of the spherical nose and Re influence the thermal flux peak. With the reduction of Re the thermal flux peak disappears and flow separates only near the edge. If the edges are rounded then separation is prevented. If Re is reduced but the radius of sphere is unchanged, then the maximal thermal flux also disappears as seen in Figure 15 and the flow does not separate.

The maximal thermal flux with laminar flow depends on $Re_{\infty} \cdot M_{\infty}^{-6}$ which is also the parameter for the viscous and inviscid flow interaction. Borovoy et al (1968a) noticed that at angles of attack $\alpha = 15$, two maximal thermal flux regions starting from the leading edge approach each other and merge into a single region at far downstream.

At $\alpha = 15$ as seen in Figure 17 a single line of flow spreading along which the thermal flux is maximal is formed in the plane of symmetry. But at $\alpha = 25$ a single thermal flux peak forms on

the front part of the model while on the downstream part two peaks are formed on each side of the center line.

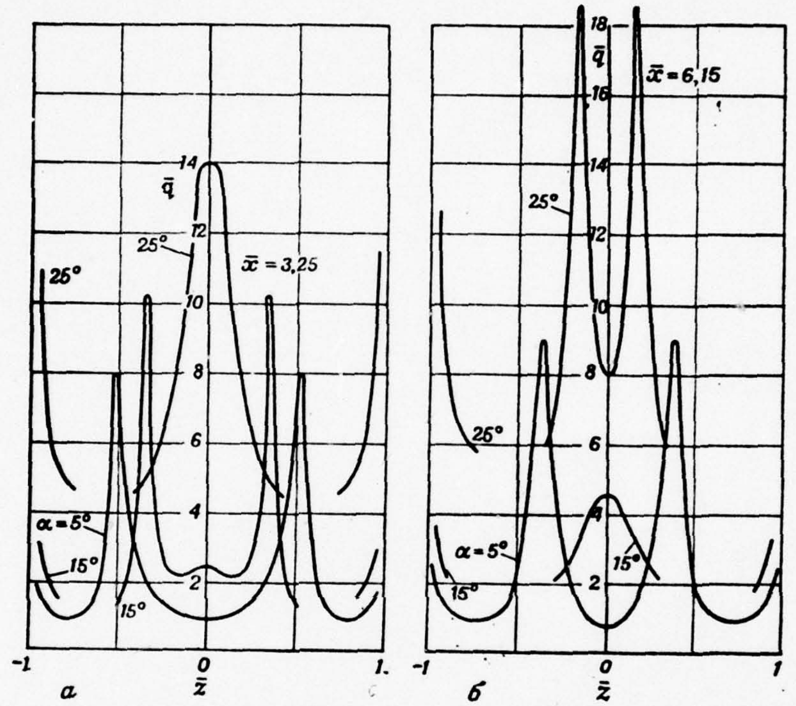

Figure 17. Thermal flux distribution along cross-section of flat side of blunt semi-cone as function of angle of attack α ; $\theta_K = 24.3°$; $M_\infty = 5$; $Re_{L\infty} = 1.1 \cdot 10^6$ (Borovoy et al , 1968b).

When the flat side of the pointed semi-cone is placed upwind then flow separates at angle of attack $\alpha > \Theta$ cone at the center. Figures 18 and 19 show a single line of flow spreading in the plane of symmetry.

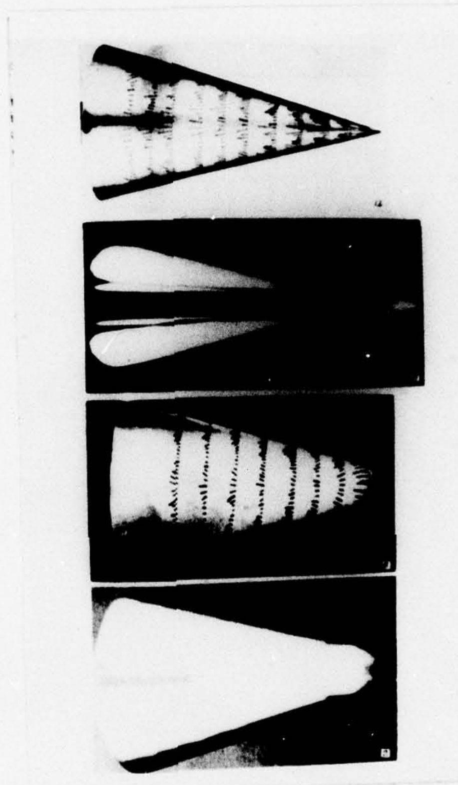

Figure 18. Semi-cone $\theta_K = 15^{\circ}$ with flat upwind side, $M_\infty = 5$, $Re_{L,\infty} = 10^{\circ}$ (Borovoy and Ryzhkova, 1971).

sharp semicone
- a) Limiting streamlines $\alpha = 30^{\circ}$
- b) Model coated w/ temp. sens. paint $\alpha = 25^{\circ}$, t = 50 c

blunt semicone
- c) Limiting streamlines $\alpha = 25^{\circ}$
- d) Model coated s/ temp. sens. paint $\alpha = 25$, t = 10 c

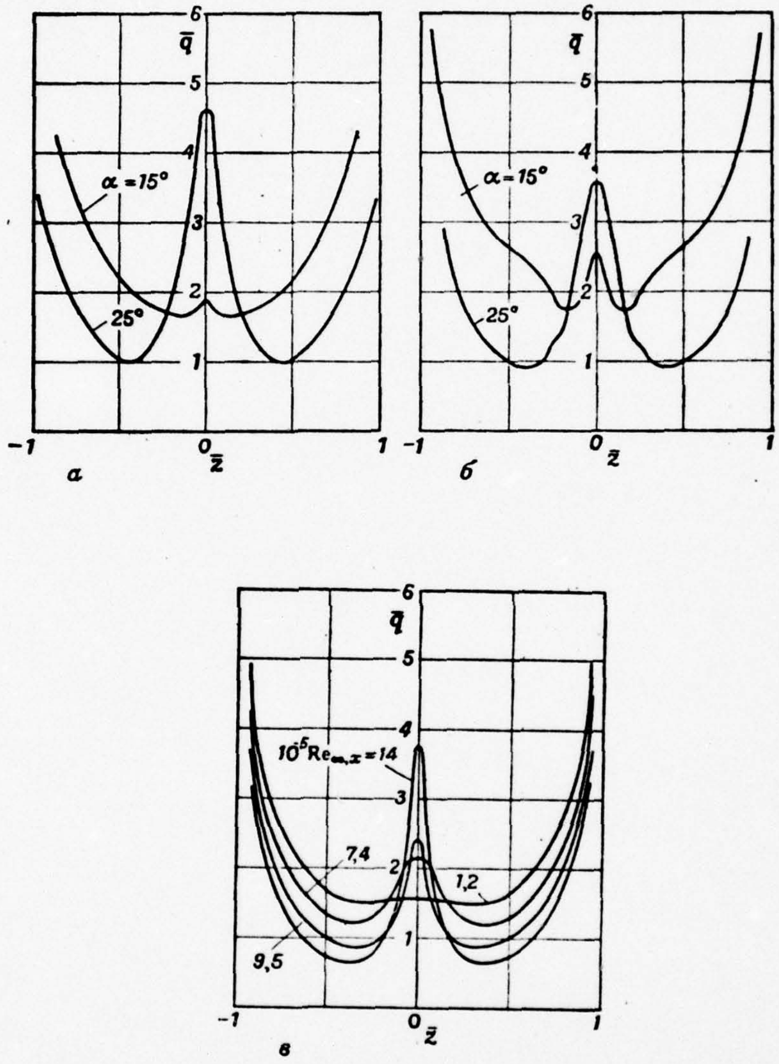

Figure 19. Thermal flux distribution along cross-section of downwind convex side of pointed semi-cone $\Theta_K = 15°$ (Borovoy and Ryzhkova, 1971).
a) $M_\infty = 5$; $Re_{\infty,x} = 0.4 \cdot 10^6$; $\bar{x} = 0.24$
b) $M_\infty = 5$; $Re_{\infty,x} = 0.77 \cdot 10^6$; $\bar{x} = 0.46$
c) $M_\infty = 6$; $\alpha = 25°$.

If Re is reduced then the lines of flow spreading disappear reducing the axial thermal flux as seen in Figure 19.
An interesting behavior of thermal flux peak on the plat side of the blunt semi-cone placed upwind is shown in Figure 20.

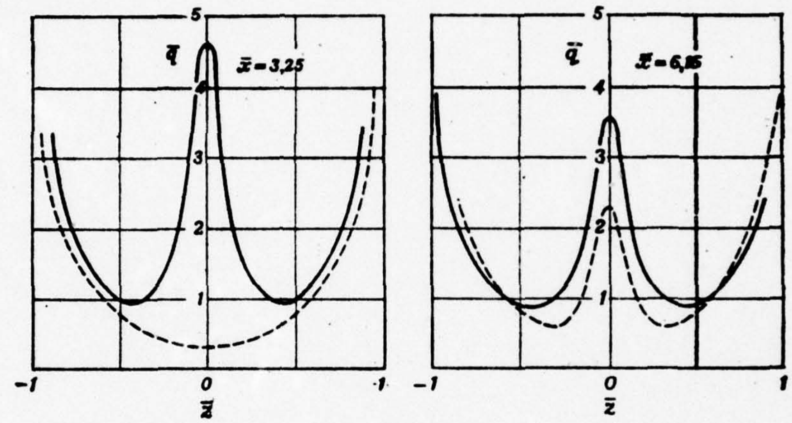

Figure 20. Thermal flux distribution along cross-section of downwind convex side of semi-cones. (Borovoy and Ryzhkova, 1971).
$\theta_k = 15°$; $\alpha = 25°$; $M_\infty = 5$; $Re_{L,\infty} = 10^4$.
------- = Blunt semicones; ________ = Pointed semicones.

The thermal flux peak disappears on the front part of the model but appears only on the apt part in smaller magnitude differing from the pointed semicone.
The flow behavior on the downwind side of the circular cone is as seen in Figure 21, similar to that of the over the downwind convex side of the semicone. Based upon the observation of the limiting streamlines it appears that the secondary separation takes place along the second line of flow confluence.

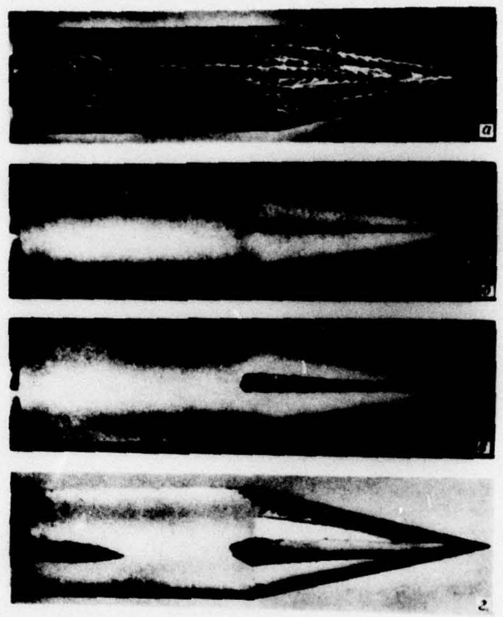

Figure 21. Cone $\theta_K = 135^0$, $M_\infty = 5$, $Re_{L,\infty} = 10^6$, $\alpha = 20^0$.
(Davlet-Kel'deyev R. Z., 1971).
a) Limiting streamlines on the downwind side;
b - t = 2S; c - t = 5S; d - t = 15S
Model with fusible temperature sensitive coating.

The thermal flux distribution on the flat downwind side of the semicone with the flat nose blunting is somewhat different, because two high thermal flux regions emanate from each corner. Similar behavior is observed as seen in Figure 22 on its downwind side of a cylinder with the elliptic cross-section and nose shaped by half of an axisymmetric ellipsoid (Morozov, 1970).

Figure 22. Regions of high thermal flux (change of temperature sensitive paint color) on downwind side of cylinder with elliptic cross-section and nose formed by half of axisymmetric ellipsoid. (Morozov, 1970).

Flow around a wedge with skewed side surface causes separation and reattachment on both surfaces facing downstream. The thermal flux peaks are observed in the attachment regions and blunting of the leading edge leads to an increase of the heat flux on the downwind side as shown in Figure 23.

Maykapar studied the phenomena of flow and heat transfer in detail on sharp edged plates, referring to the following investigations, so that basic understandings can be obtained and explained to the readers of this article.

Borovoy et al (1970) and Maykapar (1970) observed on the downside of the plat triangular plate, a single line of flow spreading, along which the peak of thermal flux prevails in the plane of symmetry.

But, Whitehead (1970) found a line of flow spreading in the forward part which becomes two closely spaced lines of flow spreading with a narrow region of separation free flow between them and two thermal flux peaks symmetric with respect to the plane of symmetry.

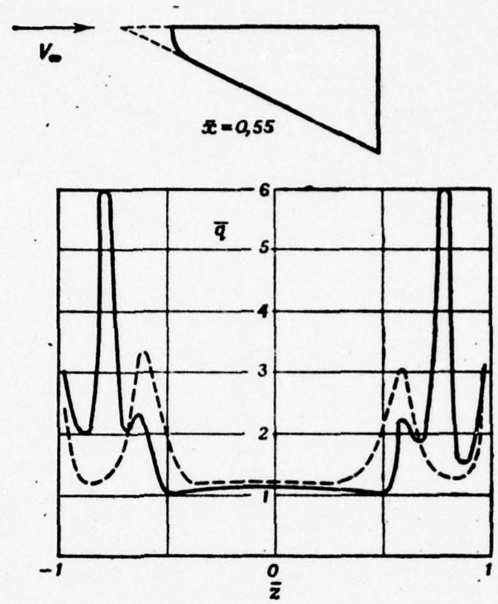

Figure 23. Thermal flux distribution along cross-section of downwind side of wedge; $M_\infty = 5$, $Re_{L,\infty} = 9.5 \cdot 10^5$. (Borovoy et al, 1970).
________ = Blunt wedge; -------- = Pointed wedge.

These two peaks approach each other and form a single peak at section closer to the apex of the plate. White head Hefner and Rao (1972) found also that the boundary layer between the lines of flow spreading behave as if they originated from the branching point.

The thermal flux variation along the center line is as follows: The thermal flux reaches its maximal value much larger than that of a flat plate computed for laminar as the distance from the apex increases then after decrease, again increases reaching the theoretical value of turbulent flow. The thermal flux along the center line decreases due to a separation free zone between the lines of flow spreading.

Maykapar does not consider that the thermal flux peak on the farward part of the plate is caused by the transition of laminar

flow to turbulent, but he could not prove it because the transition phenomena in the mixing layer was not investigated.

If the leading edges of the thick triangular plate is rounded, the flow separation can be prevented.

As shown in Figure 24, high thermal fluxes are observed,

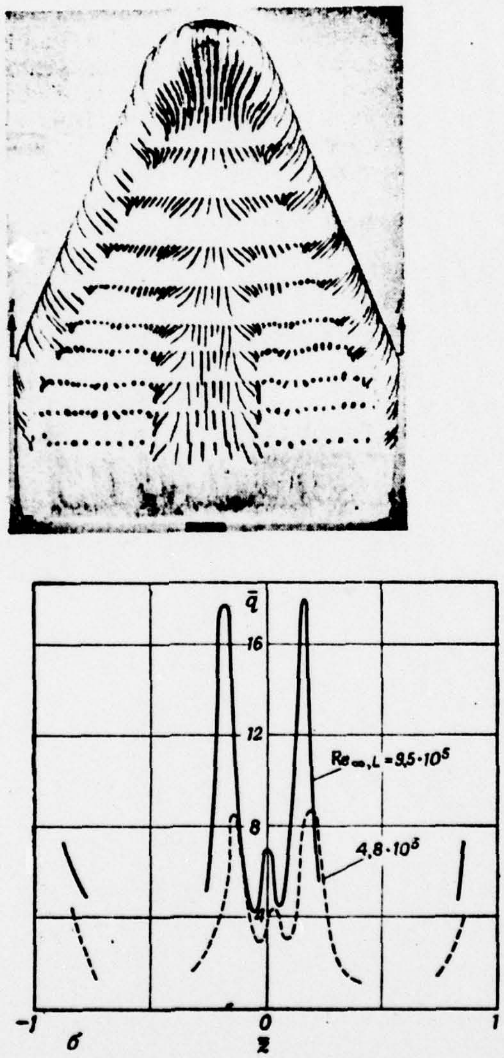

Figure 24. Limiting streamlines on downwind side of triangular flat plate with cylindrical edges and thermal flux distribution along its cross-section 1-1; $\alpha = 20°$; $M_\infty = 5$ (Borovoy et al, 1970).
a) Limiting streamlines
b) Thermal flux distribution.

on the downstream part of the plate similar to the case of the convex downwind side of the blunt semicone.

From Figure 24, it is seen also that the magnitude of this peak increases with increase of Re.

Whitehead (1971) investigated the effects of plate plan form configuration. If the plate apex is round, two narrow regions of large friction and thermal flux appear near the center line. However, if the plate leading edge is a hyperbolic shape, then lines of flow spreading, or the lines of thermal flux peak disappear. Whitehead (1971) reports that the "viscous" layer--the low density layer of the inner part of the boundary layer--has a thickness not exceeding twice the thickness of a two-dimensional boundary layer on the plate. The magnitude of this thickness decreases sharply to ~ 0.3 time of the two-dimensional thickness approaching to the triangular plate center line. However, if the leading edge shape is hyperbola then such sharp variation of viscous layer thickness does not occur. The elimination of the thermal flux peak can be achieved if the geometrical shape of the apex of the triangular plate is changed by drooping. Drooping of the triangular plate apex and hyperbola-shaped leading edge turns the flow from the edge toward the center line of the plate in continuous compression.

Employing this control technique the local angle of attack can be changed from 0° at the apex to 5° on the main part of the plate as reported by Rao (1971).

This reviewer notices that by drooping the leading edge of airfoil which is exposed to subsonic flow,laminar flow separation can be prevented (Owen and Klandler, 1953).

Maykapar summarizes his tentative conclusions in the article based upon experimental results, especially referring to Cross

and Hankey's (1969) report dealing with triangular flat plate with sharp edges as follows:

1. The separated flow characteristics depend considerably on the pressure distribution than on the distribution of the thermal flux over the surface of the body.

2. The thermal flux peaks are induced by vortices at supersonic speed. At low speeds the separated flow near the downwind side of the wing with sharp edges and cone at angles of attack is controlled by two vortices which are also observed at low supersonic speeds. Thus, it is reasoned that the thermal flux peaks at high supersonic speeds are also induced by vortices.

3. Large thermal flux peaks occur in a definite range of parameters of M and Re . Its region is located between two regions; the region of viscous and non-viscous layer interaction where separation disappears and the turbulent region. Based upon the information available in the turbulent layer reattachment region, it was reasoned that the relative magnitude of the thermal flux peaks in the turbulent layer will be smaller than in the laminar flow. However, no comparative study on magnitude of thermal flux in the viscous and non-viscous layer interaction region with respect to it in the region of the largest thermal flux peaks is available.

4. Imbedded shock increases thickness of boundary layer and causes thermal flux peak for the triangular plate. For flow over the triangular plate, the imbedded shock induces the flow toward the plate center removing the low energy gas from the middle of the plate and thickening of the boundary layer and as well as causing thermal flux peaks. Thus, together with bow wave, the imbedded shock controls separation and entire flow in the downwind region,

therefore for this case vortices are secondary phenomena.

5. The vortex pair forms as a result of flow separation from the leading edge and the vortices appear only at some distance from the apex because of the separation-free flow around the plate as Rao (1971) and Whitehead, Hefner and Rao (1972) found. Over the triangular plate flow does not separate near apex because near the apex the viscosity influence is significant in the entire disturbed flow layer and imbedded shock does not occur. The existence of separation-free flow over the windward side of the semi-cone at low Re is due to the interaction of the boundary layer with outer flow. Because the boundary layer on the down-wind side is thick forming an effective curved surface, cross flow from the upwind side is weak and there is no imbedded shock capable of causing separation.

6. Vortices are formed in the separation-free region due to transverse flow within the boundary layer as Rao (1971) found, as well as due to entropy change downstream of the shock wave reported by Maykapar (1968). No reasoning to reach this conclusion is given but Maykapar states in the article that in order to confirm the validity of these findings it is necessary to have information on the flow in the entire disturbed region.

This reviewer wishes to refer to the recent experimental findings of Korkegi (1971,72,73,75) which are the subjects of further study. Because the USSR experimental investigation is only for high heat flux phenomena and measurements of pressure, temperature, velocity and density, etc., which are important to understand the complex then dimensional flow effected by heat transfer, are missing. Although a number of USSR experimental results are reported by

Maykapar in the article he also refers to the most complete information obtained by Cross and Hankey (1969) on the flow over the triangular flat plate with sharp leading edges as well as Whitehead's (1970,71) and Whitehead, Hefner and Rao's (1972) experimental results.

In section 5 of the article; 16 USSR and 6 non-USSR references are cited (One reference is listed both in the USSR and the non-USSR reference list).

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6. Aerodynamic heating in three-dimensional regions of shock wave interaction with laminar boundary layer.

In the article and citing USSR references only, Maykapar presents the experimental studies at high speeds using simple models such as a straight and tilted cylinder mounted on a flat plate, cylinder or cone simulating a blunt wing on control surface leading edge, the transverse jet discharging into supersonic flow from the hole in the flat plate or cone, as well as triangular half-wing and blunt semi-cone mounted on the flat plate.

A. Cylinder interference with a flat plate.

As seen in Figure 25, the height of the cylinder was selected sufficiently large so that the upstream of the cylinder can be investigated accurately. The pressure distribution upstream, separation region and shape of the dividing streamline in the plane of symmetry are considered similar to those of two-dimensional flow governed by the free-interaction law. For example, C_p at the beginning of separation is proportional to $(M_\infty^2 - 1)^{-1/4}\, Re_s^{-1/4}$ (where s refers to distance measured from separation point and edge of plate) and separated region length $\sim Re_{\infty, x_0}^{1/4}$ and dividing stream line slope $\theta \sim Re_{\infty, x_0}^{-1/4}$ (where x_0 refers to distance cylinder axis from the plate edge) as reported by Borovoy and Ryzhkova (1972).

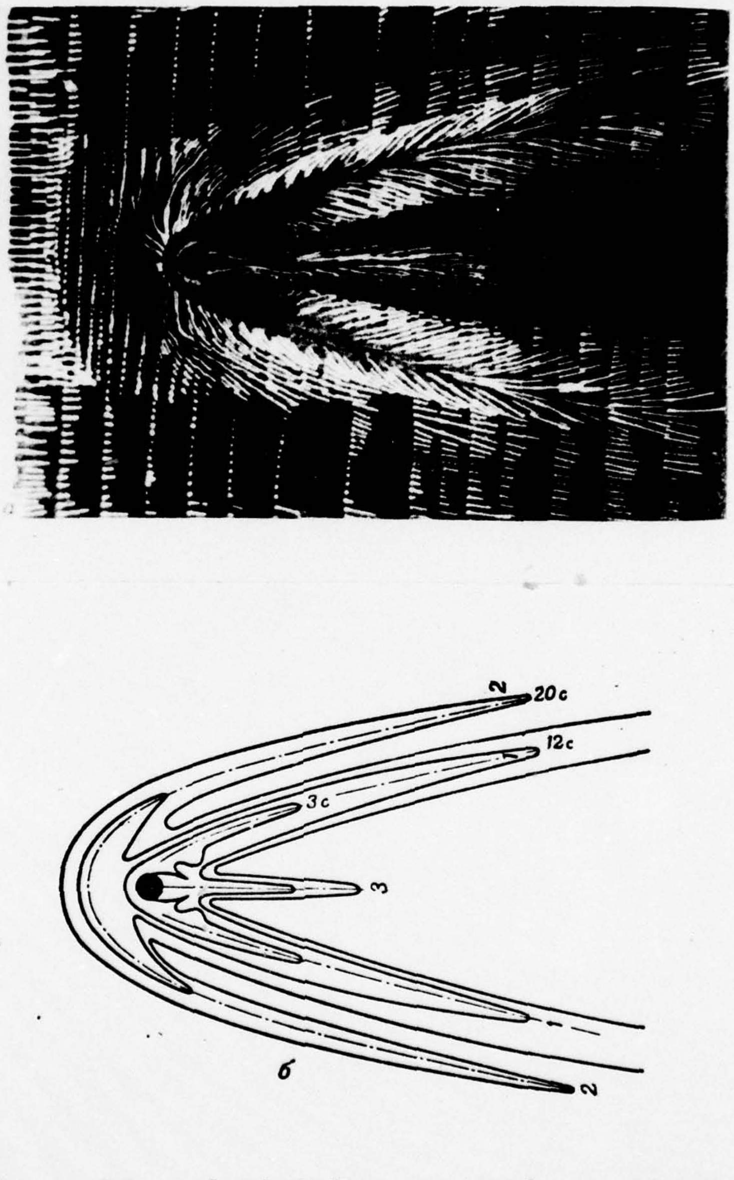

Figure 25. a) Limiting streamline pattern on plate with cylinder perpendicular to the plate surface ($M_\infty = 5$); b) Temperature-sensitive paint melting boundary (lines of constant surface temperature and thermal flux) for different times. (Borovoy and Ryzhkova, 1972).

Interaction of shock emanating from the separated region with the cylinder bow wave may lead to the appearance of thermal flux and pressure peaks on the cylinder and in the region of separated layer reattachment as reported by Tetervin (1967).
Measurements of upstream pressure distribution of the cylinder and step mounted on the plate and jet flow from the hole on the plate show that pressure distribution along the symmetric line are initially similar to each other but differ significantly approaching the cylinder, step or jet and for the jet its pressure distribution lies between those of cylinder and step as seen in Figure 26. It is necessary to refer to the investigation of Werlé et al (1970) which established a correlation of pressure distribution in the separated zone generated by forwarding step and jet issuing vertically from a hole on the plate exposed to supersonic turbulent flow to gain the much needed information on pressure distribution.

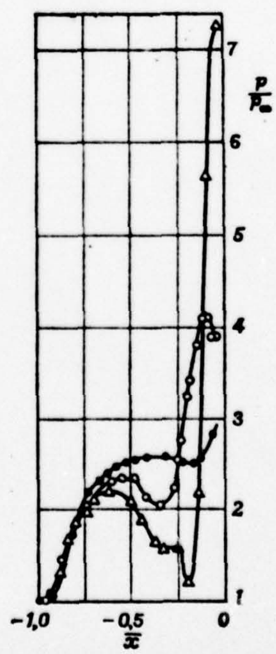

Figure 26. Pressure distribution over plate in the plan of symmetry ahead of forward-facing step, cylinder and jet, M = 3; ● = Step; O = Jet; $P_{oj} / P_{\infty} = 40$ Δ = Cylinder. (Glagolev, Zubkov and Panov, 1967).

In the three-dimensional separated flow regions, regions of supersonic flow, imbedded shocks and secondary separations are found, but the most practically important fact is the existence of thermal flux peak region whose magnitude is measured by temperature-sensitive coating as shown in Figure 27.

Figure 27. Regions of fused temperature-sensitive coating. $M_\infty = 6$ (Borovoy and Ryzhkova, 1972). a - t = 0.24 S; b - t = 1 S; c - t = 2 S; d - t = 4 S

The maximum thermal flux region is determined also by flow visualization of limiting stream line spreading as mentioned previously in section 5. The thermal flux on the flat plate reaches its maximum value in the narrow region upstream of the cylinder and its magnitude is comparable to that on the cylinder stagnation line as seen in Figure 28.

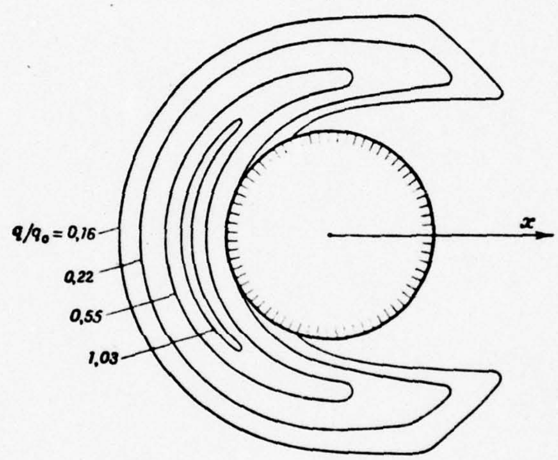

Figure 28. Lines of equal ratios q/q_0; $M_\infty = 6$;
$Re_{\infty, x_0} = 1.2 \cdot 10^3$; $T_w / T_0 = 0.6-0.9$.
q = heat flux to plate;
q_0 = heat flux to cylinder stagnation point;
(Borovoy and Ryzhkova, 1972).

Due to the presence of the cylinder the magnitude of the maximal thermal flux to the plate is larger compared to the undisturbed flat plate with no mounted cylinder as seen in Figure 29.

A second small thermal flux peak is observed upstream of the cylinder on the line 2 (Figure 25).

Judged from Figure 26 it appears that along this line pressure peak prevails.

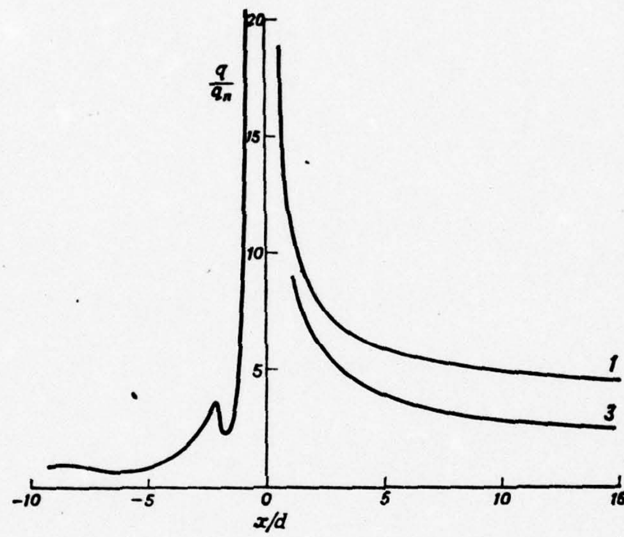

Figure 29. Heat flux to plate in symmetry plane ahead of cylinder and on lines of flow spreading aft of cylinder (lines 1,3--see Figure 25).
$M_\infty = 5$, $Re_{\infty,x_0} = 1.1 \cdot 10^6$
q_n = heat flux to smooth plate

The coordinates of lines of flow spreading of the second thermal flux maximum and line of heat flux minimum on the plate is presented in a general form, in a parameter of Re in Figure 30. The thermal flux distribution in the plane of symmetry upstream of cylinder and along the line of flow spreading is plotted in Figure 31 by Borovoy and Ryzhkova (1972).

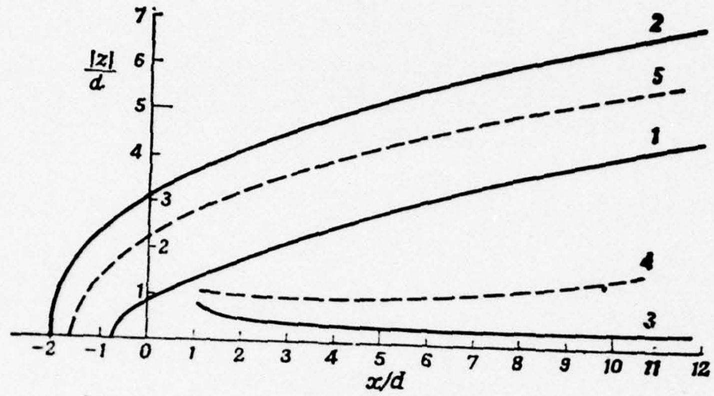

Figure 30. Coordinates of lines of flow spreading 1,3, line of second heat flux maximum 2 and lines of heat flux minimum 4.5, on plate; M_∞ = 6, Re_{∞, χ_0} = 10^5-10^6. (Borovoy and Ryzhkova, 1972).

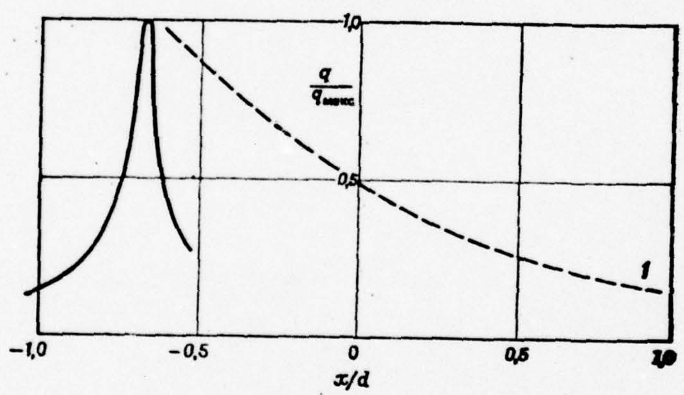

Figure 31. Heat flux distribution in plate symmetry plane and along line of flow spreading 1, M_∞ = 6. (Borovoy and Ryzhkova, 1972).

B. Cylinder on cylinder.

Flow separation phenomena over a first cylinder mounted on a second cylinder is similar to those of a cylinder mounted on a flat plate if $d/D < 0.1$ and the second cylinder has the hemispherical nose. The symbols d and D refer to diameters of first and second cylinders respectively. The same can be said of separation from the surface of a cone as seen in Figure 32.

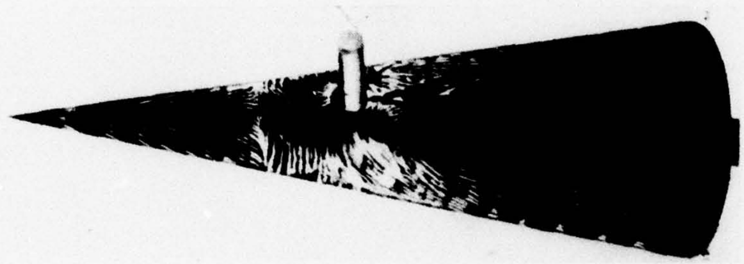

Figure 32. Pattern of limiting streamlines for cone $\theta_K = 10°$ at angle of attack $\alpha = 20°$ (upwind side) $M_\infty = 5$. (Borovoy and Ryzhkova, 1972).

Thus, the maximal heat flux upstream of the cylinder is also presented in a general form as shown in Figure 33.

If the ratio d/δ^* (where d is cylinder diameter and δ^* is displacement thickness on a smooth plate) is reduced to $\sim$1-2, the separation characteristics described thus far hold still. If $d/\delta^* < 1$ separation region extends further upstream but the number of characteristic lines in the limiting stream lines decreases leaving only a single maximum heat flux line 1 and heat flux peak upstream of the cylinder decreases sharply as shown in Figure 34.

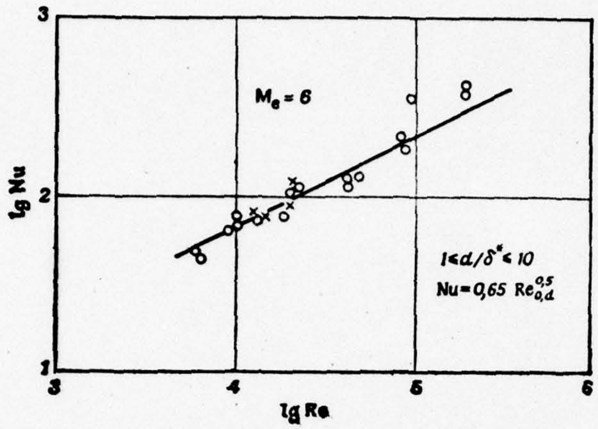

Figure 33. Maximal heat flux ahead of cylinder.

$$Nu = \frac{h_{max}\, d}{\lambda_0}, \quad Re_{0,d} = \frac{U \rho_0' d}{\mu_0}$$

(Borovoy and Ryzhkova, 1972).
λ_0, μ_0 --Coefficients of thermal conduction and viscosity corresponding to stagnation temperature;
ρ_0' = air density downstream of shock;
0 = plate; x= cone.

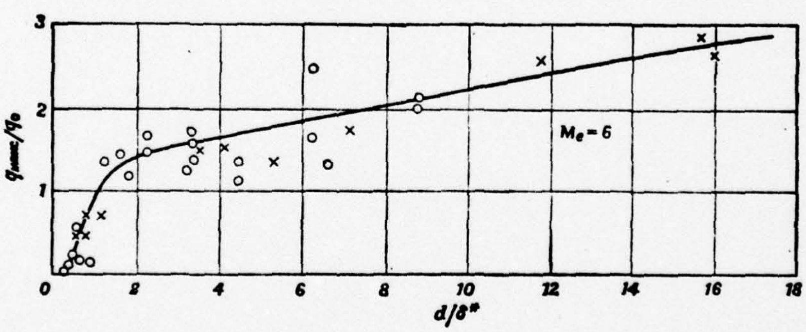

Figure 34. Maximal heat flux ahead of cylinder.
0 = plate; x = cone
(Borovoy, Ryzhkova and Sevast'yanova, 1972).

C. Tilted cylinder.

By tilting the cylinder upstream no fundamental difference is noted compared to a straight cylinder, although by tilting downstream the separated flow region is reduced in the symmetry plane. At tilt angle $\sim 45^{\circ}$ shock wave in the symmetry plane reaches the base of the cylinder and separated flow region is located along the side of the cylinder. The maximal heat flux upstream of the cylinder to the plate varies with tilt angle, similar to heat flux behavior to a yawed cylinder as reported by Borovoy and Ryzhkova (1972). The heat flux downwind surface of the cone but upstream of cylinder at angle of attack $\alpha > \theta_K$ is considerably less compared to the case of $\alpha = 0^{\circ}$ but even in this case the presence of the cylinder causes increase of the heat flux peak. (Borovoy, Ryzhkova and Sevast'yanova, 1972).

D. Jet.

Flow separation behavior upstream of the jet is very much similar to that of the cylinder as seen in Figures 35, 36 and 37 reported by Borovoy and Ryzhkova (1972).

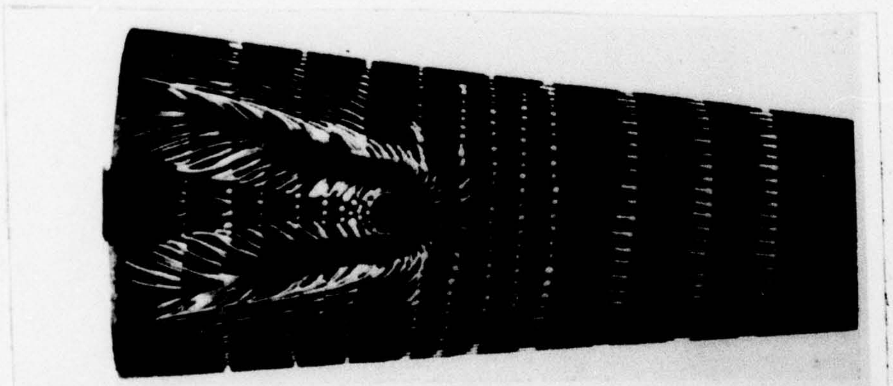

Figure 35. Pattern of limiting streamlines on cone with jet discharge. $\theta_K = 5^{\circ}$; $M_{\infty} = 5$; $\alpha = 0^{\circ}$; $P_{0j} / P_0 = 1$.

Figure 36. Pattern of limiting streamlines on downwind side of cone with jet discharge. $\theta_K = 5°$, $M_\infty = 5$, $\alpha = 10°$, $p_{oj} / p_o = 1$.

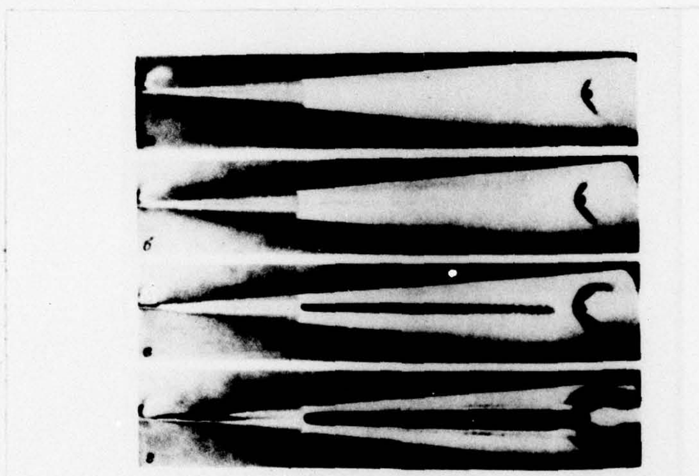

Figure 37. Boundaries of temperature-sensitive coating change. $\theta_K = 5°$, $M_\infty = 5$.
a - t = 0.5 S, b - t = 1 S, c - t = 4 S, d - t = 16 S

This reviewer notes that the experimental investigations in the USSR article just reviewed are restricted to heat transfer only, although the measurements of proper pressure, velocity, temperature and density etc. are desirable to understand the complex phenomena of three-dimensional shock interaction with boundary layer. Although limited, measurement of pressure up- and downstream of cylinder mounted on a plate and jet issued vertically to free stream at subsonic speed by Vogler (1963) may be useful to obtain the supplementary information.

E. Behavior of flow and heat transfer over a triangular half-wing with a sharp leading edge at the angle of attack.

At a sufficiently large angle of attack, flow separation occurs from the plate on which the wing is mounted as seen in Figure 38.

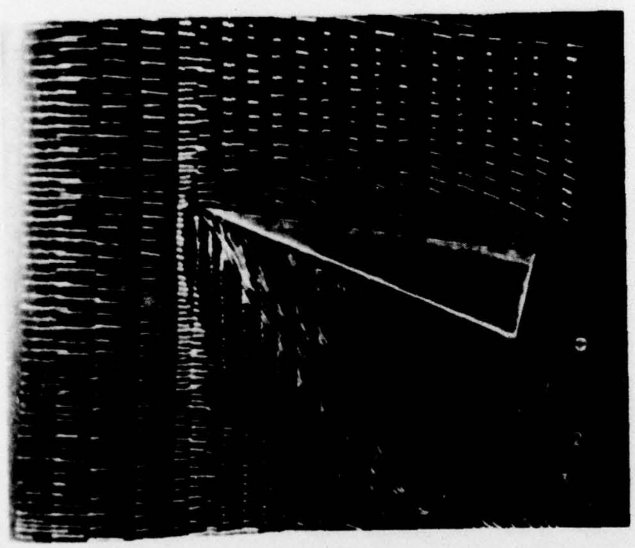

Figure 38. Pattern of limiting streamlines on flat plate with half-wing mounted on the plate, $M_\infty = 5$. (Borovoy and Sevast'yanova, 1972) (Borovoy, Ryzhkova and Sevast'yanova, 1972).

The limiting streamlines indicate that the primary reattachment occurs at line 1, the secondary separation at line 2 and reattachment at line 3. The maximum heat flux occurs on the line of reattachment and its magnitude is a function of p_{B} / p_{H} in a universal relation (where p_{B} is pressure downstream of the shock wave emanating from the half-wing leading edge and p_{H} is pressure on the plate outside the region of disturbance from the half-wing) as shown in Figure 39.

For this case the pressure ratio of apparently the most important factor in shock wave interaction with the boundary layer.

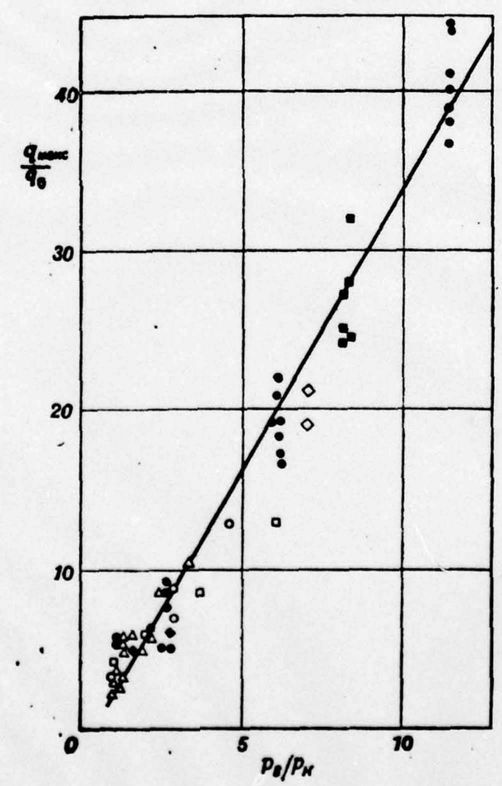

Figure 39. Dependence of ratio of maximal heat flux to plate in the separated region to heat flux to the smooth plate on the pressure ratio .(Borovoy and Sevast'yanov 1972).
△ χ = 0°, M_∞ = 3; □ χ = 0°, M_∞ = 6; ◇ χ = 30°, M_∞ = 6; ○ χ = 60°, M_∞ = 5; ● χ = 60°, M_∞ = 6; ◆ χ = 80°, M_∞ = 3; ■ χ = 0°, M_∞ = 6.

The experimental investigation for the aerodynamic heating in the USSR described by Maykapar in the article is for heat transfer to plate, and cone on which obstacles such as a cylinder are mounted. But as seen in Figure 40 the high rate of heat transfer may occur along the reattachment line on the surface of the obstacle to be mounted. This case has not been investigated in the USSR.

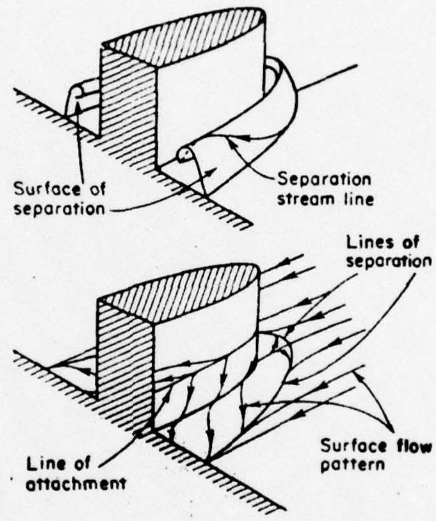

Figure 40. Limiting streamlines and trailing vortices due to separation before a strut in the boundary layer.(Dean, 1961).

In section 6 of the article only 18 USSR references are cited.

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III. Conclusions and remarks.

The authors of the article presented the developments and findings of analysis and experiments, citing 149 references with 46 figures in only 69 pages. Consequently, the presentation on the subjects is rather sketchy, giving the readers an overall outline of the recent research efforts in USSR. Therefore, a thorough and meaningful comparison of the USSR investigations with those of other contries leading to a fair appraisal of the work of the original USSR authors can be carried out only by referring to the original USSR papers. In the absence of such original USSR references, this reviewer has included remarks in the reviewed sections hoping that such comments may be useful to the readers.

Nevertheless, an attempt will be made to summarize briefly the new USSR developments, findings and experimental results here, suggesting the selected subjects for further studies.

Although the content of the article may be divided into two parts--analytical developments presented in sections 1,2,3 and 4 and experimental investigation on thermal flux peaks described in sections 5 and 6--for convenience, review of results are presented separately in each section.

1. Applicable only for high Reynolds numbers, the numerical method developed solves the N-S equations for steady and unsteady flows. The systems of N-S equations is approximated by a finite difference system and by use of a computer, high accuracy solutions are obtained. Kyshenkov's (1972b) steady flow analysis, applying the numerical method and approximated N-S equations, confirm the concept of flow pattern in the separated flow regions and the existence of a viscous mixing layer, Kyshenkov's (1970,1972a,1972b) analytical method for

viscous separated gas flow may be the subject of a comparative study with Crocco-Lees' (1952) mixing theory.

No solution for viscous separated flow over a cylinder is obtained although the separated flow region downstream of the body, including the Karman vortex street can be analyzed. No complete solution is obtained for unsteady separated flow.

2. The successful analytical solution for flow separation from the leading edge and the side of finite span wing applicable to a moderate and high angle of attack is presented. The generalized method to compute the non-linear problem of flow around the wing is developed confirming the similarity law.

3. The analytical method which is significantly different from the classical boundary layer theory is established based upon the concept of free-interaction and solving the N-S equations by asymptotic method in three regions. The three regions are, the outer region, the undisturbed boundary layer region upstream of free-interaction and the near wall viscous flow layer. The outer region is described by the first approximation by the linear supersonic theory which predicts the pressure distribution at the separation point and in the plateau pressure region but the second approximation taking account of pressure differential across the shear layer approximates more closely the real flow behavior. The approximate method is applicable for flow over a small obstacle but it is not suitable for a developed separated zone although for a simple flow a good result is obtainable.

The free-interaction theory is applied for compression flow around the corner and weak shock impingement to the boundary layer, generalizing the similarity law and flow over simply shaped surfaces such

as a plate at the angle of attack.

This new method developed by Neyland (1966, 1968, 1969, 1970, 1971a, 1971b) appears to be attractive for the thorough study parallel with analysis of Stewartson and Williams (1969).

Sychev's (1972) analysis shows that in the vicinity of separation, a free-interaction zone exists. Since it is indicated that this analysis is suitable for region of separation, further study referring to Goldstein (1948), Stewartson (195) and Brown and Stewartson (1970b) may be of value.

The analytical procedure for the reattachment zone is described and it is suggested that the Chapman-Korst condition is to be corrected by an order of $Re^{-1/4}$. This statement is worthy of careful future study.

The base flow problem is studied analytically by using Dorodnitsyn method of integral relation obtaining a reliable pressure distribution along the body surface even by the first approximation. In the base region the "blocking" effect of disturbance propagation emanating from the base upon reaching the speed of sound on the local inviscid flow streamline adjacent to the body surface exists as Neyland (1969), Matveyeva and Neyland (1967) found. A new and general similarity law taking account of this propagation of disturbance yields a reliable prediction in the regime of strong interaction of hypersonic flow with boundary layer.

Kozlova and Mikhailov (1971) show that this new similarity law, taking account of propagation of disturbance, is more reliable compared to the available similarity laws set up be Lunve (1959) and Hayes and Probstein(1959) with no consideration of disturbance propagation.

Neyland suggests further studies for the solution of compression

separated flow in connection with shift of separation point due to base pressure change and presence of reverse flow downstream of the separation point.

4. The analysis for two-dimensional separated flow using two types of approximate methods--one method using integral equation and the other, the Chapman-Korst method are presented.
The first type is supplemented by the relation connecting boundary displacement thickness distribution with outer flow characteristics. For the analysis of laminar flow, a single family of power-law velocity and the stagnation enthalpy profile of Dorodnitsyn variable as well as the single parameter family of velocity profile obtained by self-similar boundary layer equation are used. This method yields good results if the separated zone is not long.
For turbulent flow involving separation the integral method applying Crocco-Lees theory is used. Due to the high intensity of turbulent mixing with a nearly constant pressure region it is often difficult to compute by a unified scheme and results obtained are less definite, requiring experimental data.
The Chapman-Korst method yields the best results for the developed separation zone for laminar and turbulent flows such as base flow, but flow separation over smooth surface Chapman-Korst condition alone is not sufficient to determine the separation zone length and separating point, thus an additional separation criterion is needed. Gas temperature in the separated zone and time necessary to establish a stationary flow in the turbulent separated zone are evaluated.

5. Experimental investigations for high rate of heat transfer on the reattachment zone of the downwind side of the body at high speeds

and its parametric studies in M_∞, Re_∞, shape of body and angle of attack are reported. This investigation is useful for design of a high speed vehicle. The rate of heat flux is measured by change of color or transparency of the temperature sensitive coating and zones of reattachment and separation are determined by behavior of visualized limiting streamlines. The body shapes tested are cone, blunt semi-cone with blunt and sharp nose, wedge and plate. Using a sharp-edged plate, investigation is carried out most extensively, but the investigation on the effect of transition to heat transfer is missing, therefore it is suggested by this reviewer that this information needs to be supplied. For laminar flow, the maximum heat flux depends on $Re_\infty \cdot M_\infty^{-6}$. If the leading edge of a thick triangular plate is rounded then separation can be prevented.
The thermal flux peaks can be eliminated by providing a drooping or shaping hyperbola form of the apex. By drooping,flow is turned from the edge to the center line in continuous compression.
Tentatively, the following conclusions are reached:

The thermal flux peaks are caused by vortices and imbedded shocks in a definite range of M_∞ and Re_∞ in the between region of viscous with non-viscous interaction and turbulent region.

No analysis and no proper measurements of pressure (except along the center line), velocity, temperature nor density etc. are available. These are needed for understanding of the complex separated and reattaching phenomena. The author of the article refers to the most complete information obtained by Cross and Hankey (1969) on the flow over the triangular plate with a sharp leading edge and Whitehead (1970, 1971) as well as Whitehead, Hefner and Rao (1972).

6. Experimental studies for the maximum heat flux on the reattachment zone over plate and cone surfaces caused by a protruding obstacle mounted on the plate and cone and by jet flow issuing vertically to free stream from the hole on the plate and cone are reported. Most extensive studies are carried out for a cylinder mounted on a plate, but experimental investigation is also made for a triangular half-wing and blunt semi-cone mounted on a flat plate and exposed to high speed flow.

In order to evaluate the effect of a protruding obstacle on the plate, the rate of heat flux is measured with and without the obstacle. The coordinates of lines of secondary thermal flux maximum and minimum on the plate and heat flux distribution in the plane symmetry are presented. Flow separation phenomena over the first cylinder mounted on the second cylinder is similar to those of a cylinder mounted on a plate or cone if $d/D < 0.1$ where d and D are diameters of the first and the second cylinder respectively.

Heat transfer behavior depends on the ratio of d/δ^* where δ^* is displacement thickness on a smooth surface.

By tilting the mounted cylinder upstream no fundamental difference was noted compared to straight cylinder, but by tilting it downstream the separated zone is reduced in the symmetry plane and the maximum heat flux upstream of the cylinder to the plate varies with the tilt angle similar to heat flux behavior on a yawed cylinder.

At a sufficiently large angle of attack, flow separates from a plate on which a half-wing is mounted and two reattachment lines and secondary separation line are observed. On the reattachment zone heat flux is maximum and its magnitude is given in a function of p_B / p_H where p_B is pressure downstream of a shock wave emanating from the

half-wing leading edge and p_H is pressure on the outside region of disturbance from the half-wing.

No analysis and no proper measurements of pressure, velocity, temperature and density, etc. are available but are very much needed for the understanding of the complex three-dimensional flow involving separation and reattachment.

Thus, recent measurements of Korkegi (1971, 72, 73, 75) are to be studied to clarify the complex problems of the three-dimensional flow and to be applied in future studies.

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